

## **FINAL REPORT**

### **Central Massachusetts Transmission Study Long-Term Analysis**

**June 2003**

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## **FINAL REPORT EXECUTIVE SUMMARY**

This report is a follow up to a report submitted in November 2001, which identified several reliability problems for the Central Massachusetts Transmission System, and provided several short-term solutions. However, the short-term solutions provided did not address all reliability problems uncovered (due to both study scope and time constraints), nor did they provide long-term solutions to the problems they did address. To this end, a long-term planning study (2004 – 2015) was undertaken to address the remaining reliability problems in the Central MA transmission system. This report documents the results of that study.

### **Existing Reliability Problems**

The major reliability problems identified for the Central MA transmission system are as follows:

- Overload of two 115-69 kV autotransformers (50 MVA) at Millbury substation (T1 & T2), for loss of one onto the other during heavy load conditions.
- Overload of two 115-69 kV autotransformers (56 MVA) at Ayer substation (T4 & T6) for loss of one onto the other during heavy load conditions.
- Overload of two 345-115 kV autotransformers (448 MVA) at Sandy Pd substation (T1 & T2) for several contingencies during heavy load conditions.
- Low voltage at Webster St 115kV substation (Worcester) for several contingencies.
- Low voltage at Ayer 69 kV substation for a Double Circuit Tower contingency (2.5 mi of exposure).
- Low voltage at Flagg Pd 115 kV substation for a Double Circuit Tower contingency (8.2 mi of exposure).
- Overduty of Shrewsbury 69 kV breaker (I35).

### **Proposed Solutions**

The following transmission upgrades are proposed to solve most of the reliability problems identified above:

- Eliminate overload of Millbury T1 & T2 (50 MVA) by replacing with larger transformers (56 MVA). Cost: \$1.5M
- Eliminate overload of Ayer T4 & T6 (56 MVA) by transferring load from Ayer to Pratts Jct substation, and adding two 115-69 kV transformers (56 MVA) at Pratts Jct. Cost: \$1.4M
- Eliminate overload of Sandy Pd T1 and T2 by installing two 345-115 kV transformers at Wachusett substation, in Boylston MA. This upgrade also eliminates the Ayer 69 kV voltage problem. To accommodate the new 345-115 kV transformation at Wachusett, several other transmission facilities in Central MA need to be upgraded. These facilities include overhead lines, breakers, and terminal equipment (both 115 and 69 kV). Cost (w/ associated upgrades): \$32.3M
- Eliminate over-duty of Shrewsbury 69 kV breaker by replacing breaker. Cost: \$0.43M
- Total cost of proposed upgrades: \$35.6M (99% of the upgrades are required in 2004 and 2005).

### **Reliability Problems Not Addressed in This Study**

Not all reliability problems identified in this study were addressed, since these problems are currently being addressed in separate studies. The reliability problems not addressed in this study are as follows: 1) Webster St - Low Voltage, and 2) Flagg Pd – Low Voltage. Reports on these studies are forthcoming.

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### **APPENDIX A – Loadflow Summaries – Steady State Analysis**

### **APPENDIX B – Loadflow Summaries – Stability Analysis**

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## **1.0 SUMMARY**

This report is a follow up to a report submitted in November 2001, which identified several reliability problems for the Central Massachusetts Transmission System, and provided several short-term solutions. However, the short-term solutions provided did not address all reliability problems uncovered (due to both study scope and time constraints), nor did they provide long-term solutions to the problems they did address. To this end, a long-term planning study (2004 – 2015) was undertaken to address the remaining reliability problems in the Central MA transmission system. This report documents the results of that study.

### **Existing Reliability Problems**

The major reliability problems identified for the Central MA transmission system are as follows:

- Millbury T1 & T2 overload for loss of one onto the other during heavy load conditions. These two 115-69 kV autotransformers (50 MVA) provide 66% of the power fed out of Millbury 69 kV substation to nearby loads (e.g. Westboro, N. Grafton, etc).
- Ayer T4 & T6 overload for loss of one onto the other during heavy load conditions. These 115-69 kV autotransformers (56 MVA) provide 100% of the power fed out of Ayer 69 kV substation to surrounding loads (e.g. Groton, Devens, Pepperell).
- Sandy Pd T1 & T2 overload for several contingencies during heavy load conditions. These two 345-115 kV autotransformers (448 MVA) are a critical supply to the Central Massachusetts 115 kV transmission system. Failure of these two transformers could have a negative impact on transmission facilities outside New England.
- Webster St 115kV Low voltage – Drops below 0.90 pu for several contingencies. Webster St serves approximately 90 MW of load in Worcester during peak load conditions.
- Ayer 69 kV low voltage – Drops below 0.9 pu for a Double Circuit Tower contingency (2.5 mi of exposure). Ayer servers approximately 90 MW of load to surrounding areas (e.g. Groton, Peperell, Devens) during peak load periods.
- Flagg Pd 115 kV low voltage – Drops below 0.9 pu for a Double Circuit Tower contingency (8.2 mi of exposure). Flagg Pd serves approximately 90 MW of load in Fitchburg during peak load periods.
- Shrewsbury 69 kV Breaker is over-dutied – Interrupting capability is 7.5 kA, 3-phase fault duty is 8.4 kA.

### **Reliability Problems Not Addressed in This Study**

Not all reliability problems identified in this study were addressed, since these problems are currently being addressed in separate studies. The reliability problems not addressed in this study are as follows:

- 1) Webster St - Low Voltage: Being addressed in separate study (will go away if sufficient distribution load at Webster St is transferred to Vernon Hill substation)
- 2) Flagg Pd – Low Voltage: Being addressed in a joint study of the SEVT, SWNH, and Monadnock region working with ISO-NE, NU, and VELCO.

Reports on these studies are forthcoming.

### **Solution Options**

The remaining reliability problems identified were addressed in this study. Solutions to these problems were developed and are described below:

- Millbury T1 & T2 Overload Problem – Solution Options:

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1. Install 4th Millbury 115-69 kV Autotransformer Into Dedicated 115 kV Breaker Position (\$3.8M)
2. Install 4th Millbury 115-69 kV Autotransformer, Tap to Q-143, Remove I-35 (\$2.06M)
3. Replace Millbury T1 & T2 with 56 MVA Autotransformers (\$1.5M)
4. Convert X-24 69 kV Circuit to 115 kV (\$14.95M)

Recommendation: Option 3 (Least Cost - \$1.5M)

- Ayer T4 & T6 Overload Problem – Solution Options:
  1. Install Two Additional 115-69 kV Transformers at Ayer (\$4.55M)
  2. Transfer  $\frac{1}{2}$  Prospect St Load From V-22E to U-21S, Add Two 115-69 kV Autos at Pratts (\$1.4M)
  3. Convert V-22 69 kV Circuit to 115 kV (\$13.7M)

Recommendation: Option 2 (Least Cost – \$1.4M)

- Sandy Pd T1 & T2 Overload Problem – Solution Options:
  1. Pratts Jct - Install 2 new 345-115 kV autos (448 MVA), and associated upgrades (\$32.3M)\*
  2. Wachusett - Install 2 new 345-115 kV autos (448 MVA), and associated upgrades (\$32.2M)\*
  3. Quinsigamond Jct. - Install 2 new 345-115 kV autos (448 MVA), and associated upgrades (\$36.1M)\*

Recommendation: Option 2 (Least Cost – \$32.2M)\*

- Shrewsbury 69 kV Breaker Over-duty Solution Options:
  1. Do Nothing – Shrewsbury substation may removed be removed in 4 years, based on current MECO plans. (\$0.0M)
  2. Replace with IC = 40 kA, 115 kV breaker (\$0.43M).

Recommendation: Option 2 (Safety – \$0.43M)

\*Present Value using present worth factor of 7.79%

The above upgrades are the lowest cost of the alternatives developed, and provide long-term solutions to the problems addressed (i.e. solutions for the time period out to 2015).

### **For Further Study**

Although the solutions recommended in this study provide for long-term reliability of the Central Massachusetts transmission system (i.e. out to year 2015), load flow simulations indicate that low voltage problems may develop in the Northboro Rd area at the end of the study period (i.e. 2015). Therefore, the next planning study conducted for Central Massachusetts should focus on this issue.

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## List of All Transmission Upgrades Proposed in this Study

The following is a complete list of the transmission upgrades proposed in this study.

**Table 1.1: List of Proposed Transmission Upgrades for Central MA**

Transmission Upgrade	Year	Study Grade Cost Estimate (\$M)				Post-Upgrade Thermal Ratings Norm/LTE (MVA)
		Capital	O&M	Removal	Total	
Replace Millbury T1 & T2 (115-69 kV) w/ 56 MVA Transformers – Salvage existing T1 & T2 for use at Wachusett station. Does not require bus upgrades.	2004	1.400	0.025	0.075	1.500	66/84*
Transfer 1/2 of Prospect St load from V-22E to U-21S 69kV line - Convert Prospect 69 kV supply to two radial feeds, one from V-22S, the other from U-21S. Both lines are served from Pratts Jct.	2004	0.085	0.000	0.000	0.085	N/A
Install 2 additional 115-69 kV Transformers (56 MVA) at Pratts Jct - Results in total of five 115-69 kV transformers at Pratts Jct. Requires bus upgrades also.	2004	1.390	0.005	0.005	1.400	66/84*
<b>Upgrade Wachusett Substation -</b> 1.) <b>Install two 345-115 kV autos (448 MVA)</b> – Loop 343 and 314 lines in and out of station. Install 345 kV & 115 kV bkr + 1/2 scheme. 2.) <b>Install two additional 115-69 kV transformers</b> - Utilize existing Millbury T1 and T2 transformers. 3.) <b>Replace all five 69 kV breakers</b> - Replace w/ IC=40 kA breakers, due to over-duty.	2005	25.400	0.300	0.050	25.75	<b>345/115 Autos:</b> 520/580* <b>115/69 Autos:</b> 57/62
<b>Plus Associated Upgrades</b> (Upgrades caused by new 345-115 kV transformation at Wachusett). Listed Below:						
Replace all 8 Pratts Jct 69 kV breakers – Replace with IC=40 kA, due to over-duty.	2005	0.770	0.035	0.035	0.840	N/A
Upgrade O-141N [Quinsigamond Jct – Greendale Sub] 115 kV line – Reconducto with 636 ACSS. Does not require terminal upgrades.	2005	0.550	0.025	0.175	0.750	259/269
Upgrade O-141 [Greendale Sub – Nashua St] 115 kV line – Reconducto with 636 ACSS. Does not require terminal upgrades.	2005	0.550	0.025	0.175	0.750	259/269
Upgrade P-142N [Wachusett – W Boylston] 115 kV line – Reconducto with 1113 ACSS. Does not require terminal upgrades.	2008	0.150	0.006	0.019	0.175	366/440
Upgrade M-39 69 kV line – Reconducto with 795 ACSR. Requires complete rebuild of M-39 (6' Triangular Structures). Does not require terminal upgrades.	2005	0.800	0.050	0.150	1.000	139/171
Upgrade N-40 69 kV line – Reconducto with 795 ACSR. Requires complete rebuild of N-40 (6' Triangular Structures). Also requires terminal upgrades at Pratts Jct.	2005	0.970	0.055	0.155	1.180	139/171
Upgrade Rolfe Ave 115 kV Breaker – Replace with 2000 A Breaker, IC = 40 kA, due to thermal overload and insufficient interrupting capability.	2005	0.350	0.006	0.010	0.366	321/321 (O/H line rating)
Upgrade W-175 115 kV [Carpenter Hill – W Charlton] – Reconducto w/ 1590 ACSR. No terminal equipment upgrades required.	2005	0.405	0.053	0.018	0.475	287/330
Upgrade W-23E Disconnect Switch (236N) – Replace with a 2000 A Switch.	2005	0.020	0.000	0.000	0.020	124/124 (O/H line rating)
Upgrade W Boylston Sub (MUNI) to meet NPCC Criteria – Includes replacement of 115 kV breaker (2000 A, 50 kA).	2005	0.425	0.015	0.010	0.450	N/A
Install High Speed Protection on O-141 and P-142 115 kV Lines – At Greendale, Wachusett, Boylston, and Pratts Jct Substations.	2005	0.425	0.015	0.000	0.440	N/A
Replace Shrewsbury 69 kV breaker – IC= 19 kA	2004	0.400	0.006	0.020	0.426	N/A
<b>TOTALS:</b>		<b>34.165</b>	<b>0.621</b>	<b>0.896</b>	<b>35.63</b>	

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\* Expected Ratings

## **2.0 GEOGRAPHIC DIAGRAM OF REGION**

A geographic diagram of the Central Massachusetts transmission system is given below.

**Figure 2.1: Geographic Diagram of Central Massachusetts Transmission System**

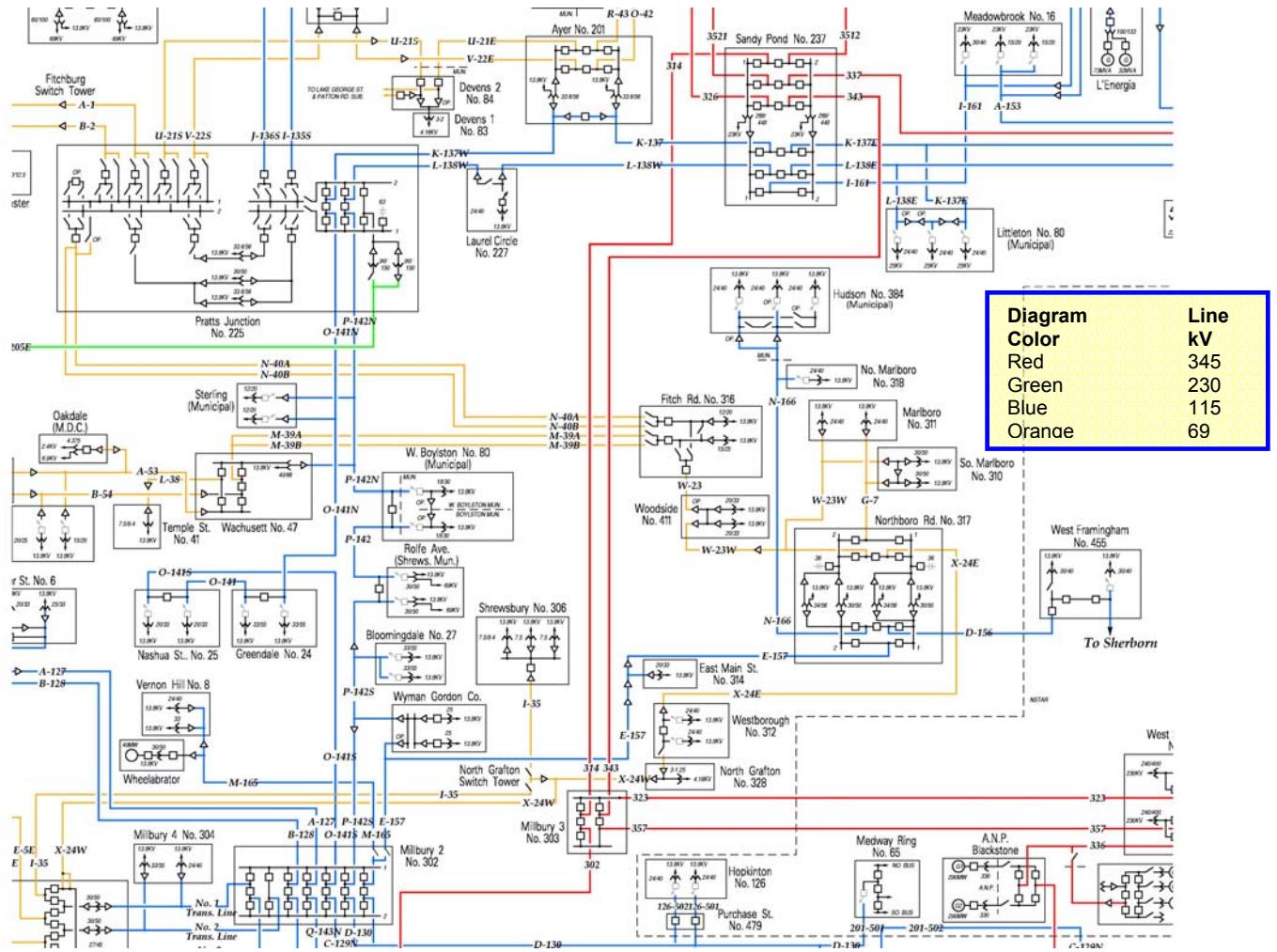
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## 3.0 ONE-LINE DIAGRAM OF REGION

A one-line diagram of the Central Massachusetts transmission system is given below.

**Figure 3.1: One-Line Diagram of Central Massachusetts Transmission System**



## 4.0 ASSUMPTIONS

The study included the following assumptions:

- Power Factor of all retail load (MECO and municipal) in the Central Massachusetts region will be at least 0.99 lagging during heavy load conditions<sup>1</sup>.
- Greater Metro West (GMW) upgrades (close through W-23 69 kV line at Woodside, Woodside 69kV breaker, 2<sup>nd</sup> Wachusett 115/69 kV xfmr) in-service in 2003.
- D-156 115 kV terminal equipment at W Framingham substation (owned by NSTAR) upgraded in

<sup>1</sup> This power factor (0.99 lagging) corresponds to the minimum load power factor developed by the NEPOOL Voltage Task Force (VTF) in 2002 for the Central Massachusetts area, during peak load conditions.

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2003. This upgrade increases the thermal rating of the D-156 circuit, to that of the NEP rating (Summer LTE = 269 MVA).

- V-174 115 kV Line [Carpenter Hill – Millbury] to be reconducted in June 2003 with 1590 ASCR.
- Sandy Pd 115 kV breakers I-161 & 1612 upgraded to 63 kA (IC) in 2003.
- Any new 115/69 kV autotransformer to be purchased by NEP will have a summer LTE rating equal to 150% of its maximum nameplate rating (e.g. 56 MVA transformer will have a summer LTE rating of 84 MVA). The standard specification for 115/69 kV autotransformers calls for a summer LTE rating of at least 150% of maximum nameplate MVA.
- Any new 345/115 kV autotransformer to be purchased by NEP will have a summer LTE rating equal to 130% of its maximum nameplate rating (e.g. 448 MVA transformer will have a summer LTE rating of 582 MVA). The standard specification for 345/115 kV autotransformers calls for a summer LTE rating of at least 130% of maximum nameplate MVA.
- %Z of new 345/115 kV autotransformer to be specified as follows:

345-115 kV (H-X):	%Z = 7.45% on 268 MVA base
345-23 kV (H-Y):	%Z = 50% on 268 MVA base
115-23 kV (X-Y):	%Z = 40% on 268 MVA base

The preceding values are all standard impedance values for National Grid 345/115 kV autotransformers (New England).

- EMC research facility in-service in 2005.
- Devens Municipal Summer Peak Load is as follows (from forecast provided by Devens on 3/25/02):

Year	Summer kVA
2002	19,555
2003	23,962
2004	26,953
2005	28,282
2006	29,377
2007	31,992
2008	33,718
2009	35,295
2010	36,872

- All of Devens Municipal load will be normally supplied via the U-21E 69 kV transmission line (i.e. Ayer Side). Upon loss of U-21E, all Devens load will be thrown over to the U-21S 69 kV transmission line (Pratts Jct side).
- Any substation or transmission line upgrade proposed in this study, requiring an in-service date of 2005 or earlier, will be initiated no later than 9/11/04 and finished no later than 1/1/06, assuming the PDS for the subject work is issued no later than March 2003. Meeting these time constraints allows for tax savings resulting from a bonus 20-yr tax depreciation schedule implemented by the US Congress to spur the economy.
- Solution to Flagg Pd 115 kV voltage problem, currently being addressed in a joint study for the SEVT, SWNH, and Monadnock region, will be implemented before 1/1/06.
- Fitch Rd 69 kV Substation rebuild completed by 1/1/06.

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## 5.0 BASE CASE LOADFLOWS

Both short-term and long-term base case loadflows were developed for this study. Summer peak load cases were developed for the following years:

1. 2003
2. 2006
3. 2010
4. 2015

For each year given above, the following transmission biases within New England were modeled:

1. High East-West Transfers (2200 MW)
2. High West-East Transfers (800 MW)

In addition, shoulder peak (75% peak load) cases (both E-W and W-E biases) were developed for year 2006, along with a light load (50% summer peak) case for year 2006.

Therefore, a total of 11 base case loadflows were developed for this study. All 11 cases originated from the 2005 summer peak case of the ISO-NE year 2000 submittal to the FERC. The following table provides more details on the cases developed for this study.

**Table 5.1: Base Case Details – Steady State Analysis**

Case Name	Year	Load Level	NEPOOL Load (GW)	NEW ENGLAND INTERFACE TRANSFERS (MW)						
				E-W (2200)	N-S (2700)	PH II (2000)	SEMA/RI (2200)	BI (3600)	NNE-Sc (2550)	CI
03s-ew-100%	2003	Summer Peak	25.2	2211	2079	2000	2204	2920	2054	1162
03s-we-100%				-776	1681	2000	155	3307	1452	-266
06s-ew-100%	2006	Summer Peak	25.8	2195	2092	2000	2183	2951	2158	1555
06s-we-100%				-785	2092	2000	43	3600	1979	-678
06s-ew-75%		75% peak	19.3	2197	2354	1500	1790	2316	1802	1819
06s-we-75%				-799	1221	1500	395	2709	704	-237
06s-50%		Light load	12.6	2206	1414	1200	1520	1385	1194	1297
10s-ew-100%	2010	Summer Peak	27.0	2210	2081	2000	2209	2922	2233	1185
10s-we-100%				-779	2368	2000	-179	3610	2046	-664
15s-ew-100%	2015	Summer Peak	29.9	1912	2306	2000	2203	3392	2361	814
15s-we-100%				-825	1817	2000	329	3592	1996	-408

More detailed summaries for both cases are given in Appendix A of this report.

The NEPOOL load value represented in the 2003 peak load cases is equal to that experienced during summer peak load conditions in 2001 (25.2 GW NEPOOL Load). Note that this NEPOOL load value is higher than that forecast in the 2002 CELT Report for year 2003. The 2002 CELT Report forecasts a peak NEPOOL load of 24.8 GW for 2003. This is 1.6% lower than the actual peak load experienced in 2002. Consequently, the higher load experienced in 2002 was utilized for this analysis.

The NEPOOL load values represented in all 2006 and 2010 cases are based on the peak load forecast in the 2002 CELT Report for 2006 and 2010, respectively.

The NEPOOL load values represented in the 2015 cases were based on the peak load forecast in the 2002 CELT Report for year 2011(2002 CELT report does not provide forecasts for years later than 2011), then scaled up by 1.8% per year (compounded) to get to 2015. 1.8% load growth is equal to the load growth forecast in the 2002 CELT Report between years 2002 and 2011.

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## 6.0 CONTINGENCY LIST

**Table 6.1: Contingencies Tested**

CONTINGENCY NAME	KV	DESCRIPTION
<b>HVDC Facilities</b>		
Phase II	-	Sandy Pond HVDC Converter – 2000 MW Maximum
<b>345 kV Transmission Lines</b>		
301/302	345	Millbury – Carpenter Hill – Ludlow
314	345	Sandy Pond – Millbury
315	345	W Farnum – Brayton Pt
323	345	Millbury – W Medway
325	345	W Medway – W Walpole
326	345	Scobie – Sandy Pond
326 + Y151 SPS	345 +115	Scobie – Sandy Pond + Y151 [Pelham jct- G192 Tap]
3361	345	Sherman Rd – ANP Blackstone
337	345	Tewksbury – Sandy Pond
338	345	Tewksbury – Woburn
339	345	Tewksbury – Golden Hills + GH T1 (345/115kV)
340	345	Vermont Yankee – Coolidge
343	345	Sandy Pd – Millbury
347	345	Sherman Rd – Lake Rd
347 + WOOD SPS	345 + 115	Sherman Rd – Lake Rd + Woodriver SPS (Opens 115kV bkr at Woodriver)
357	345	Millbury – W Medway
389	345	W Medway – W Walpole
394	345	Seabrook – Ward Hill – Tewksbury
394 + Y151 SPS	345 + 115	Seabrook – Ward Hill – Tewksbury + Y151 [Pelham jct- G192 Tap]
<b>345 kV Transformers</b>		
Sandy Pd T1	345/115	Sandy Pond Transformer #1
Sandy Pd T2	345/115	Sandy Pond Transformer #2
Golden Hills T1	345/115	Golden Hills Transformer #1
Golden Hills T2	345/115	Golden Hills Transformer #2
Carpenter Hill T1	345/115	Carpenter Hill Transformer #1
Walpole T345A	345/115	W Walpole Transformer 345A
<b>345 kV Breaker Failures</b>		
Millbury 1402 BF	345	314 + 302 lines
Millbury 302 BF	345	301/302 + 357
Millbury 343 BF	345	343 + 323
Millbury 4357 BF	345	343 + 357 lines
Millbury 314 BF	345	314 + 323
Sandy Pd 337 BF	345	337 + Sandy Pd T2
Sandy Pd 343 BF	345	343+ Sandy Pd T2
Sandy Pd 326 BF	345	326 + Sandy Pd T1
Sandy Pd 2643 BF	345	326 + 343
Sandy Pd 314 BF	345	314 + Sandy Pd T1
Tewks 3739 BF	345	337 + 339 + Golden Hills T1
Tewks 3894 BF	345	338 + 394
Sherman 142	345	336S + 328
W Medway 101	345	336N + Medway T345B (345/230 kV)
W Medway 104	345	357 + Medway T345B (345/230 kV)
W Medway 105	345	357 + 344
W Medway 107	345	323 + Medway T345A (345/230 kV)
W Medway 108	345	323 +325
W Medway 111	345	389 + Medway T345A (345/230 kV)
VY 79-40	345	340 + 379
<b>345 kV Double Ckt Towers</b>		
325+344 DCT	345	325 + 344
<b>230 kV Transmission Lines</b>		
240-601	230	W Medway – Framingham
282-602	230	W Medway – Waltham
E-205E	230	Bear Swamp – Pratts Jct.
<b>230/115 kV Transformers</b>		
Tewks T3	230/115	Tewksbury Transformer #3
Tewks T4	230/115	Tewksbury Transformer #4
Tewks T5	230/115	Tewksbury Transformer #5
<b>115 kV Transmission Lines</b>		
455-507	115	W Framingham – Sherburn
A-127W	115	Harriman – Webster St
A-127E	115	Webster St – Millbury

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CONTINGENCY NAME	kV	DESCRIPTION
B-128	115	Harriman – Millbury
C-129N	115	Millbury – Depot St – Beaver Pnd
D-130	115	Millbury – Depot St – Medway
Q-143N	115	Millbury – Uxbridge
R-144	115	Millbury – Woonsocket
I-135N	115	Bellows Falls – Flagg Pd
I-135S	115	Flagg Pd – Pratts Jct
J-136N	115	Bellows Falls – Flagg Pd
J-136S	115	Flagg Pd – Litchfield Tap – Pratts Jct
K-137E	115	Sandy Pd – Tewksbury
K-137 + SPS	115	Sandy Pd – Ayer + Ayer T4 (115/69 kV) + SPS to throw Devens Load to Pratts
K-137W + SPS	115	Ayer – Pratts Jct + Ayer T6 (115/69 kV) + SPS to throw Devens Load to Pratts
L-138E	115	Sandy Pd – Tewksbury
L-138W	115	Sandy Pd – Pratts Jct
O-141N	115	Pratts Jct – Greendale + Wachusett T2 (115/69 kV)
O-141	115	Greendale – Nashua St
O-141S	115	Nashua St – Millbury
P-141N	115	Pratts Jct – W Boylston
P-141	115	W Boylston – Rolfe Ave
P-141S	115	Rolfe Ave – Millbury
D-156	115	Northboro Rd – W Framingham
E-157/M-165	115	Millbury – Northboro Rd + Millbury – Vernon Hill
U-173	115	Carpenter Hill – Snow St
V-174	115	Carpenter Hill – Millbury
W-175	115	Carpenter Hill – Palmer
W-175 + M SPS	115	Carpenter Hill – Palmer + Millenium SPS
<b>115 kV Capacitor Banks</b>		
Millbury Cap #1	115	Millbury 63 MVAr Cap Bank
Millbury Cap #2	115	Millbury 63 MVAr Cap Bank
Northboro Cap #1	115	Northboro 54 MVAr Cap Bank
Pratts Jct Cap #1	115	Pratts 63 MVAr Cap Bank
<b>115 kV Breaker Failures</b>		
NB E157 BF	115	Northboro Rd: E-157 + T2/4 + 69kV cap #1 (32 MVAr)
NB D156 BF	115	Northboro Rd: D-156 + T1/3 + 69kV cap #2 (32 MVAr)
Hudson BF	115	Hudson: N-166 + H-160 + Nboro Rd: T2/4 + 69kV cap #1 (32 MVAr)
<b>115 kV Double Ckt Towers</b>		
127W+128 DCT	115	A-127W + B-128
127E+128 DCT	115	A-127E + B-128
337+A153 DCT	115 + 345	337 + A-153
337+I161 DCT	115 + 345	337 + I-161
I135S+J136 DCT	115	I-135S + J-136S
137+138W DCT	115	K-137 + Ayer T4 + L-138W + Devens SPS (2.6 miles)
137W+138W DCT	115	K-137W + Ayer T6 + L-138W + Devens SPS (13 miles)
141S+142S DCT	115	O-141S + P-142S
141S+142 DCT	115	O-141S + P-142
141N+142 DCT	115	O-141N + P-142
141N+142N DCT	115	O-141N + P-142N
Q-143N+S DCT	115	Q-143N + Q-143S
<b>115/69 kV Transformers</b>		
Millbury T1	115/69	Millbury Transformer #1 (50 MVA)
Millbury T2	115/69	Millbury Transformer #2 (50 MVA)
Millbury T3	115/69	Millbury Transformer #3 (45 MVA) + 63 MVAr Cap Bank
Northboro Rd T1+T3	115/69	Northboro Rd Transformers #1 + #3 + 32 MVAr Cap Bank #1 (69 kV)
Northboro Rd T2+T4	115/69	Northboro Rd Transformers #2 + #4 + 32 MVAr Cap Bank #2 (69 kV)
Pratts T6 + T7	115/69	Pratts Jct Transformers #6 + #7
Pratts T4	115/69	Pratts Jct Transformer #4
Pratts T7	115/69	Pratts Jct Transformer #7
Ayer T4	115/69	See contingency K-137W
Ayer T6	115/69	See contingency K-137
Wachusett T2	115/69	See contingency P-142N
<b>69 kV Transmission Lines</b>		
A-1S	69	Pratts Jct – Otter River
B-2S	69	Pratts Jct – Park St (Gardner)
U-21E	69	Ayer – Devens
U-21W	69	Devens – Pratts Jct
V-22E	69	Ayer – Prospect St
V-22W	69	Prospect St – Pratts Jct
W-23E	69	Northboro Rd – Woodside
W-23W	69	Woodside – Fitch Rd

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CONTINGENCY NAME	kV	DESCRIPTION
M-39	69	Fitch Rd – Wachusett
N-40	69	Fitch Rd – Pratts Jct
O-42	69	Ayer – Pepperell Power
R-43	69	Ayer – Groton St.
A-53	69	Wachusett – Holden
B-54	69	Wachusett – Cooks Pd
E-5E	69	Millbury – Spencer
F-6E	69	Millbury – Spencer
S-19	69	Millbury – Webster
X-24E	69	Northboro Rd – Westboro
X-24W	69	Westboro – Millbury
I-35	69	Millbury – Shrewsbury
<b>69 kV Double Ckt Towers</b>		
E5E+F6E DCT	69	E-5E + F-6E
X24W+I35 DCT	69	X-24W + I-35
<b>69 kV Capacitor Banks</b>		
Nboro Cap1	69	Northboro Rd Cap #1 (32 MVar)
Nboro Cap2	69	Northboro Rd Cap #2 (32 MVar)
Generators		
Mystic 7	345	
Wheelabrator	115	
Seabrook	345	
Pilgrim	345	
Millstone G3	345	
Millennium	115	

### 7.0 THERMAL AND VOLTAGE CRITERIA

The study results were analyzed using criteria set forth in the Transmission Planning Guide for the New England Power Company.

The following tables identify the steady state voltage criteria applied in the study:

**Table 7.1: Min and Max Voltage Criteria Applied in Study**

CONDITION	345 & 230 kV		115 kV & Below	
	Low Limit (p.u.)	High Limit (p.u.)	Low Limit (p.u.)	High Limit (p.u.)
Normal Operating	0.98	1.05	0.95	1.05
Post Contingency & Automatic Actions	0.95	1.05	0.90	1.05

**Table 7.2: Δ Voltage Criteria Applied in Study**

CONDITION	345 & 230 kV (%)	115 kV & Below (%)
Post Contingency & Automatic Actions	5.0	10.0
Switching of Reactive Sources or Motor Starts (All elements in service)	2.0 *	2.5 *
Switching of Reactive Sources or Motor Starts (One element out of service)	4.0 *	5.0 *

\* These limits are maximums which do not include frequency of operation. Actual limits will be considered on a case-by-case basis and will include consideration of frequency of operation and impact on customer service in the area.

**Notes to Tables 7.1 and 7.2:**

- a. Voltages apply to facilities which are still in service post contingency.
- b. Site specific REMVEC or NEPEX operating restrictions may override these ranges.
- c. These limits do not apply to automatic voltage regulation settings which may be more stringent.

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d. These limits only apply to NEP facilities.

The following table identifies the thermal criteria applied in the study.

**Table 7.3: Thermal Criteria Applied in Study**

SYSTEM CONDITION	TIME FRAME	MAXIMUM ALLOWABLE FACILITY LOADING
Pre-contingency (All lines in)	Continuous	Normal Rating
Post-contingency	Less than 15 minutes after contingency occurs	STE Rating*
	More than 15 minutes after contingency occurs	LTE Rating

\* Post-contingency loadings above LTE but below STE were considered acceptable as long as prompt manual action (local phase shifter adjustment, manual generation runback) or immediate automatic action (special protection system (SPS) operation, automatic generation runback) could reduce all facility loadings below LTE within 15 minutes.

## 8.0 RESULTS FOR EXISTING SYSTEM (2003)

### 8.1 Thermal Results

The following table provides thermal results for contingencies tested on both 2003 base cases.

**Table 8.1: Thermal Results – Existing System (2003)**

Facilities Loaded at or above 100% of LTE Rating			BASE CASE	CONTINGENCY (Loss of)
Overloaded Facility	KV	%LTE		
Sandy Pd T1	345/115	140*	03s-ew-100%	Sandy Pd 337 BF
		139*	03s-we-100%	
		113	03s-ew-100%	Sandy Pd 343 BF
		109	03s-ew-100%	Sandy Pd T2
		101	03s-ew-100%	Sandy Pd 314 BF
Pratts Jct T8A	230/115	107**	03s-ew-100%	Phase II
Millbury T1	115/69	105	03s-ew-100%	455-507
		103		M-165/E-157
		112		Millbury T2 (115/69 kV)
		107		Millbury T3 (115/69 kV)
		106		NB D156 BF
Millbury T2	115/69	105	03s-ew-100%	455-507
		103		M-165/E-157
		112		Millbury T1 (115/69 kV)
		107		Millbury T3 (115/69 kV)
		106		NB D156 BF
Ayer T4 [115/69kV xfmr]	115	112	03s-we-100%	K-137
		112	03s-ew-100%	
Ayer T6 [115/69kV xfmr]	115	122	03s-we-100%	K-137W
		121	03s-ew-100%	

\* The DAL rating of Sandy Pond T1 is exceeded as well.

\*\* Overload of Pratts T8A goes away if the ACE “zero” crossing that occurs every 10 minutes in New England is taken advantage of (in reality, there could be +/- 300 MW bandwidth in the ACE so the “zero” crossing every 10 minutes may actually be +300 MW). The upshot of this is that, following the loss Phase II (2000 MW), 1700 MW of this source loss will

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be restored in New England within 10 minutes. With 1700 MW of the 2000 MW restored in 10 minutes, Pratts Jct T8A will not overload out to 2015. In the time period prior to the 10 minute "zero" crossing, an intertial loadflow solution (phase II source loss of 2000 MW picked by inertia of all machines in Eastern Interconnection) shows that the post-contingency loading on Pratts T8A is 184 MVA, which identical to the LTE rating of the subject transformer. An inertial loadflow solution applies for about 0.5 seconds after the contingency. In summary, taking advantage of the ACE "zero" crossing every 10 minutes, as well as the intertial pickup expected during the time period prior to the 10 minute "zero" crossing, the existing Pratts Jct T8A provides sufficient thermal capability

### 8.2 Voltage Results

The following table provides voltage results for contingencies tested on both 2003 cases.

**Table 8.2: Voltage Results – Existing System (2003)**

BUSES W/ VOLTAGE VIOLATIONS		Voltage	BASE CASE	CONTINGENCY
Bus	KV	Pu		(Loss of)
Pratts Jct	230	0.978	03s-we-100%	Base Case
		0.91		Phase II
		0.89	03s-we-100%	K-137 + L138W DCT + SPS
		0.93	03s-ew-100%	
Flagg Pd	115	0.86	03s-ew-100%	I-135S + J-136S DCT
		0.88	03s-we-100%	
Barre	115	0.86	03s-we-100%	A-127E
		0.84	03s-we-100%	A-127E + B-128 DCT
		0.89	03s-ew-100%	
Paxton	115	0.85	03s-we-100%	A-127E
		0.83	03s-we-100%	A-127E + B-128 DCT
		0.89	03s-ew-100%	
Webster St	115	0.84	03s-we-100%	A-127E
		0.89	03s-ew-100%	A-127E + B-128 DCT
		0.82	03s-we-100%	
		0.88	03s-ew-100%	
		0.88	03s-we-100%	NB D156 BF
		0.88	03s-we-100%	NB D156 BF
Prospect St - Ayer Side (Leominster)	69	0.77	03s-we-100%	K-137+L-138W DCT
		0.81	03s-ew-100%	
		0.85	03s-we-100%	K-137
		0.87	03s-ew-100%	
Pepperell Power	69	0.77	03s-we-100%	K-137+L-138W DCT
		0.82	03s-ew-100%	
		0.86	03s-we-100%	K-137
		0.87	03s-ew-100%	
Ayer	69	0.79	03s-we-100%	K-137+L-138W DCT
		0.84	03s-ew-100%	
		0.87	03s-we-100%	K-137
		0.88	03s-ew-100%	
Chaffins (B-54 Tap to Holden)	69	0.89	03s-we-100%	K-137+L-138W DCT
Cooks Pond (B-54 Tap )	69	0.94	03s-we-100%	BASE CASE
		0.89	03s-we-100%	K-137+L-138W DCT
Groton St	69	0.77	03s-we-100%	K-137+L-138W DCT
		0.82	03s-ew-100%	
		0.86	03s-we-100%	K-137
		0.87	03s-ew-100%	

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BUSSES W/ VOLTAGE VIOLATIONS		Voltage	BASE CASE	CONTINGENCY
Bus	KV	Pu		(Loss of)
Groton Muni (O-42 Tap)	69	0.78	03s-we-100%	K-137+L-138W DCT
		0.83	03s-ew-100%	
		0.86	03s-we-100%	
		0.88	03s-ew-100%	
Groton Muni (R-43 Tap)	69	0.77	03s-we-100%	K-137+L-138W DCT
		0.82	03s-ew-100%	
		0.85	03s-we-100%	
		0.87	03s-ew-100%	
James River Paper	69	0.77	03s-we-100%	K-137+L-138W DCT
		0.82	03s-ew-100%	
		0.86	03s-we-100%	
		0.88	03s-ew-100%	

### 8.3 Short-Circuit Results

**Table 8.3: Short Circuit Results – Existing System (2003)**

Substation	Delivery Voltage (kV)	3-PH Peak RMS (kA)	1-PH Peak RMS (kA)	Breaker I.C. (kA)
Ayer	115	20.6	15.8	40.0
Ayer	69	11.7	11.0	19 - 22
Fitch Rd	69	16.3	13.1	40.0
Greendale	115	9.5	7.6	25.1
Meadow St (Spencer)	69	10.2	4.7	31.5
Millbury 5	69	27.0	27.0	31.5
Millbury 2	115	27.1	24.2	50.0
Millbury 3	345	33.2	23.7	37.0 - 50.0
Nashua St	115	9.5	7.7	40.0
Northboro Rd	115	14.1	10.8	25.1 - 43.0
Northboro Rd	69	18.3	16.4	21.0 - 31.5
Park St	69	3.2	2.1	22.0
Pratts Junction	115	21.9	20.5	40.0
Pratts Junction	69	19.0	19.0	19.0 - 21.0
Prospect St (existing 69 kV)	115	5.4	2.9	19.0
Rolfe Ave (Shrewsbury)	115	14.5	11.4	17.6
Sandy Pond	115	40.8	44.5	63
Sandy Pond	345	28.5	22.8	50.0
Shrewsbury	69	8.4	7.9	7.5
Wachusett	69	11.4	11.0	19.0 - 20.0
Webster St	115	8.9	7.7	31.4
Westboro	69	12.4	7.6	22.0
Woodside	69	15.4	11.0	31.5

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## 8.4 Summary of Existing Problems

**Table 8.4: Summary of Existing Problems (2003)**

Location	Criteria Violated	Description
1. Ayer	Thermal	T4 & T6 Autos (115-69 kV) overloaded for loss of one onto the other.
2. Pratts Jct	Voltage	Low Voltage on 230 kV bus for base case (all-lines-in), and K137+L138W DCT contingency.
3. Millbury	Thermal	T1 & T2 (115-69 kV Transformers) overloaded for loss of each other.
4. Sandy Pond (Ayer)	Thermal	T1 & T2 (345-69 kV Transformers) overloaded. T1 overloads for loss of T2, and several 345 kV BF contingencies. T2 overloads following 314 BF contingency.
5. Webster St (Worcester) 6. Paxton (Muni) 7. Barre	Voltage	Low Voltage on 115 kV bus following A-127E contingency and A-127E+B-128 DCT contingency.
8. Shrewsbury	Short Circuit	Overdutied 69 kV breaker I35.
9. Chaffins (Holden Muni)	Voltage	Low Voltage on 69 kV bus following K137+L138W DCT contingency.
10. Cooks Pd (Worcester)		
11. Ayer 69 kV Area	Voltage	Low Voltage on 69 kV System (O-42, R-43 lines supplied from Ayer) following K137+L138W DCT contingency.
12. Flagg Pd	Voltage	Low Voltage on 115 kV bus following I-135S + J-136S DCT contingency.

## 9.0 SOLUTION OPTIONS

Of the problems identified in this study, several are currently being addressed in separate studies. The problems that will be addressed in other studies are as follows:

- Webster St Low Voltage – Being addressed in the Worcester Grid Study (New 230-115 kV transformer being contemplated for Barre to eliminate low voltage problem at Webster St).
- Flagg Pd 115 kV Low Voltage – Being addressed in the SEVT/SWNH/Monadnock area study.

No solutions to the preceding problems are therefore proposed in this document.

Solutions to the remaining problems are proposed in the following sections.

### 9.1 Alternatives Developed to Eliminate Overload of Millbury T1 & T2 (115-69 kV)

Millbury T1 and T2 115-69kV transformers overload for loss of each other during stressed system conditions. To solve this problem, the following options were considered:

- 1 Install a 4th 115-69 kV transformer at Millbury.
- 2 Replace Millbury T1 & T2 with 100 MVA transformers, and purchase 100 MVA spare.
- 3 Replace Millbury T1 & T2 with 56 MVA transformers
- 4 Off-load the 69 kV system at Millbury by converting X-24 69 kV circuit to 115 kV.

The following sections describe each alternative.

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### **9.1.1 Install 4<sup>th</sup> Millbury 115-69 kV Autotransformer Into Dedicated 115 kV Breaker Position**

Installing a 4<sup>th</sup> 115-69 kV autotransformer (56 MVA) at Millbury and terminating it into a dedicated 115 kV breaker position is practically very difficult. The difficulty arises from the 115 kV breaker failure contingency that results if the 4<sup>th</sup> transformer is installed in the empty 115 kV breaker position at Millbury. If the 4<sup>th</sup> transformer is installed in this position, a 115 kV tie breaker failure will take out both the 4<sup>th</sup> 115-69 kV transformer and the existing Millbury T2. Moreover, this contingency will split the ring bus on the 69 kV side. This design is unacceptable. To eliminate this design problem, one of the two options must be exercised:

- 1      Install new 115 kV bay at Millbury on the east side of the substation.
- 2      Swap A-127E 115 kV line position at Millbury with empty breaker position, such that no 115 kV breaker failure takes two 115-69 kV transformers out of service at the same time.

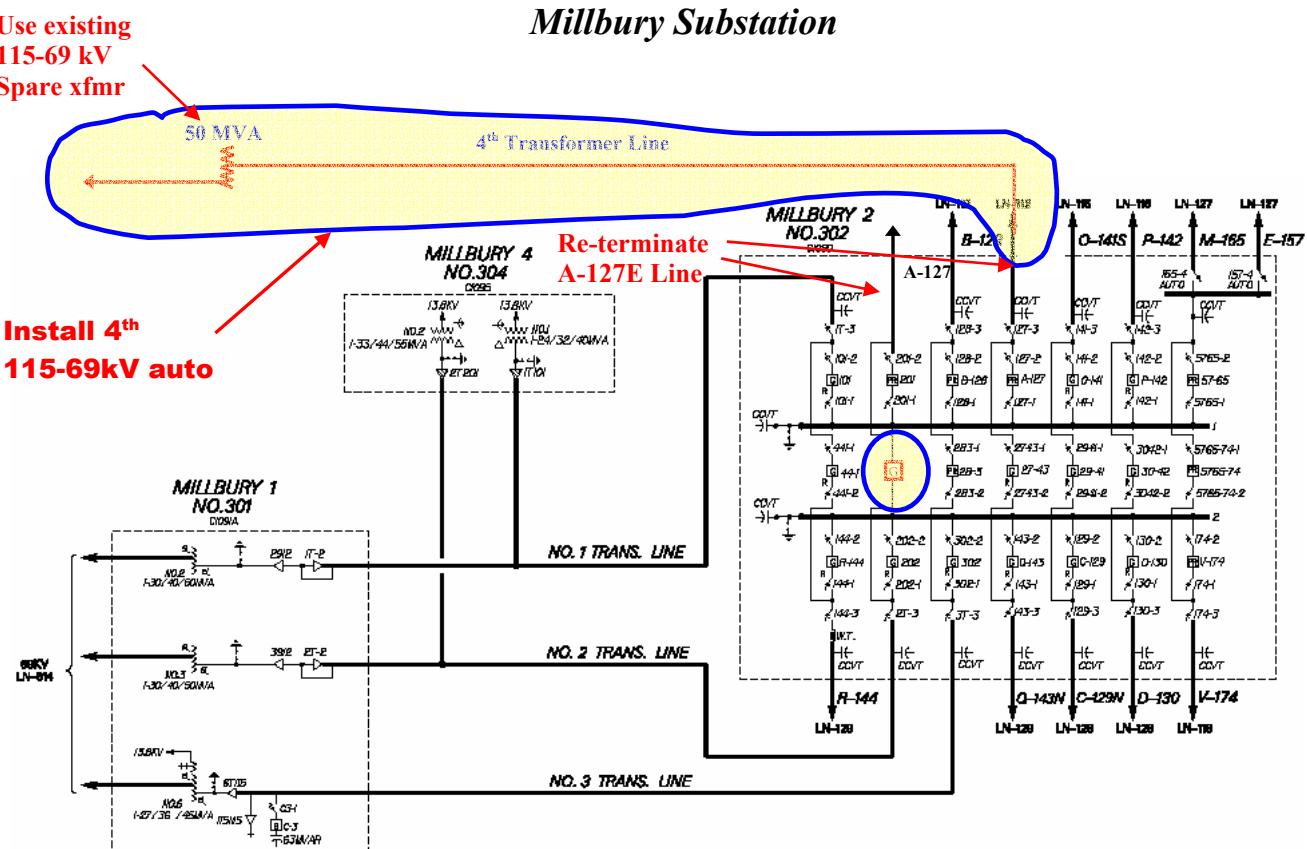
Installing a new 115 kV bay on the east side of Millbury Substation is not feasible due to wetlands issues. Re-terminating the A-127E 115 kV line into the vacant breaker position at Millbury is feasible, however it is very expensive (\$1M). Re-terminating the A-127E line is therefore proposed for this option. Note that re-terminating the B-128 line, as well as the A-127E at Millbury was also investigated (i.e. shifting A-127 and B-128 down by one bay, and installing the 4<sup>th</sup> transformer line in the vacated bay). However, this option would be more expensive than just re-terminating the A-127E line.

It is further proposed that the existing 115-69 kV spare transformer be utilized for the 4<sup>th</sup> Millbury 115-69 kV transformer. The reason being that the existing spare has a relatively low rating (72 MVA summer LTE), which is lower than many 115-69 kV transformers in the National Grid system. This may cause the existing spare to overload if it is installed in place of one of the higher rated transformers. To eliminate this problem, it is proposed that the existing spare be utilized for the 4<sup>th</sup> Millbury 115-69 kV transformer, and that a new transformer be purchased (with a higher rating) to restore the spare. Loadflow results indicate that the existing spare does not overload if used in the Millbury T4 position. Note that the existing spare is presently stored at Millbury substation so no transportation costs would be required.

The following diagram shows the interconnection.

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**Figure 9.1: Install 4<sup>th</sup> 115-69 kV Auto at Millbury**



## Study-Grade Cost Estimates

	Millbury 115 kV Substation	Millbury 69 kV Substation*	Transmission Line	Totals
Capital:	\$600,000	\$2,000,000	\$1,000,000	\$3,600,000
O&M:	\$0	\$195,000	\$0	\$195,000
Removal:	\$0	\$5,000	\$0	\$5,000
Total:	<b>\$600,000</b>	<b>\$2,200,000</b>	<b>\$1,000,000</b>	<b>\$3,800,000</b>

\* Utilizes existing 50 MVA spare at Millbury. Relocates existing underground cables for X-24 Line.

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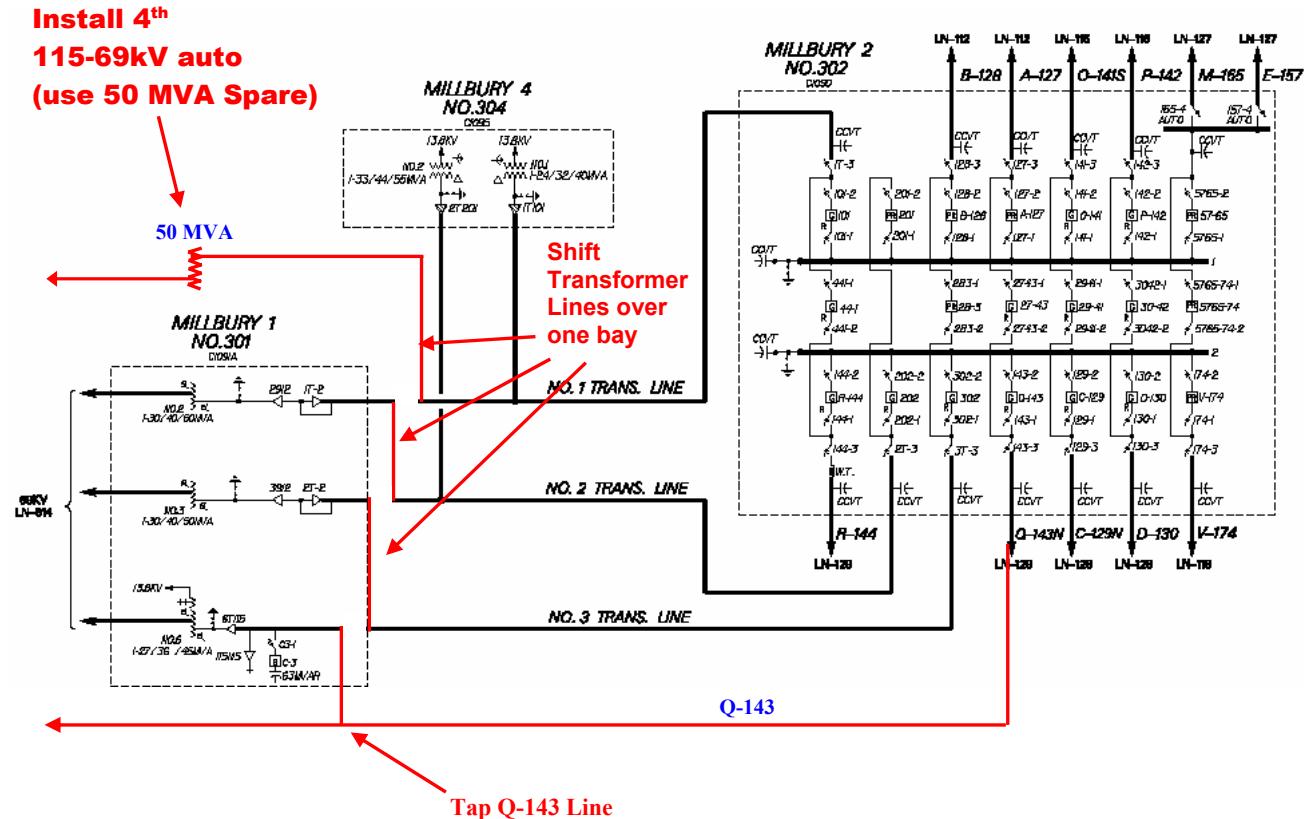
## 9.1.2 Install 4<sup>th</sup> Millbury 115-69 kV Autotransformer – Tap to Q-143, Remove I-35

An alternate method of installing the 4<sup>th</sup> Millbury 115-69 kV autotransformer (56 MVA) is to connect it directly to the Q-143 line, not to a dedicated 115 kV breaker position. This eliminates 115 kV substation costs at Millbury #2. Costs can be further reduced at Millbury 305 (69 kV substation) by removing the I-35 69 kV transmission line from Millbury to North Grafton. Removing this section of I-35 frees up a 69 kV breaker position at Millbury, thus eliminating the need to install another position for the 4<sup>th</sup> Millbury autotransformer. To avoid a 69 kV Breaker Failure problem at Millbury (i.e. breaker failure resulting in loss of Millbury T4 and T1), W-24W must be re-terminated in the existing I-35 position. Note that the existing I-35 position only has one underground cable getaway, where the X-24W position has two, and therefore half the thermal capacity. However, loadflow results indicate that one underground cable for X-24W is sufficient (i.e. cable does not overload for any contingency). Therefore, X-24W can be re-terminated into the existing I-35 position, and the 4<sup>th</sup> Millbury transformer can be terminated in the existing X-24W position. Also, loadflow results indicate that I-35 line can be supplied directly from the X-24W line at the N Grafton Switch Tower, without creating any system problems.

To connect to Q-143, the existing 115 kV Transformer lines at Millbury would be shifted down by one bay (e.g. existing Transformer line #1 would be shifted over to new T4, existing Transformer Line #2 would be shifted over to T1, etc.). Existing T3 then would connect to Q-143. This connection results in less line cross-overs.

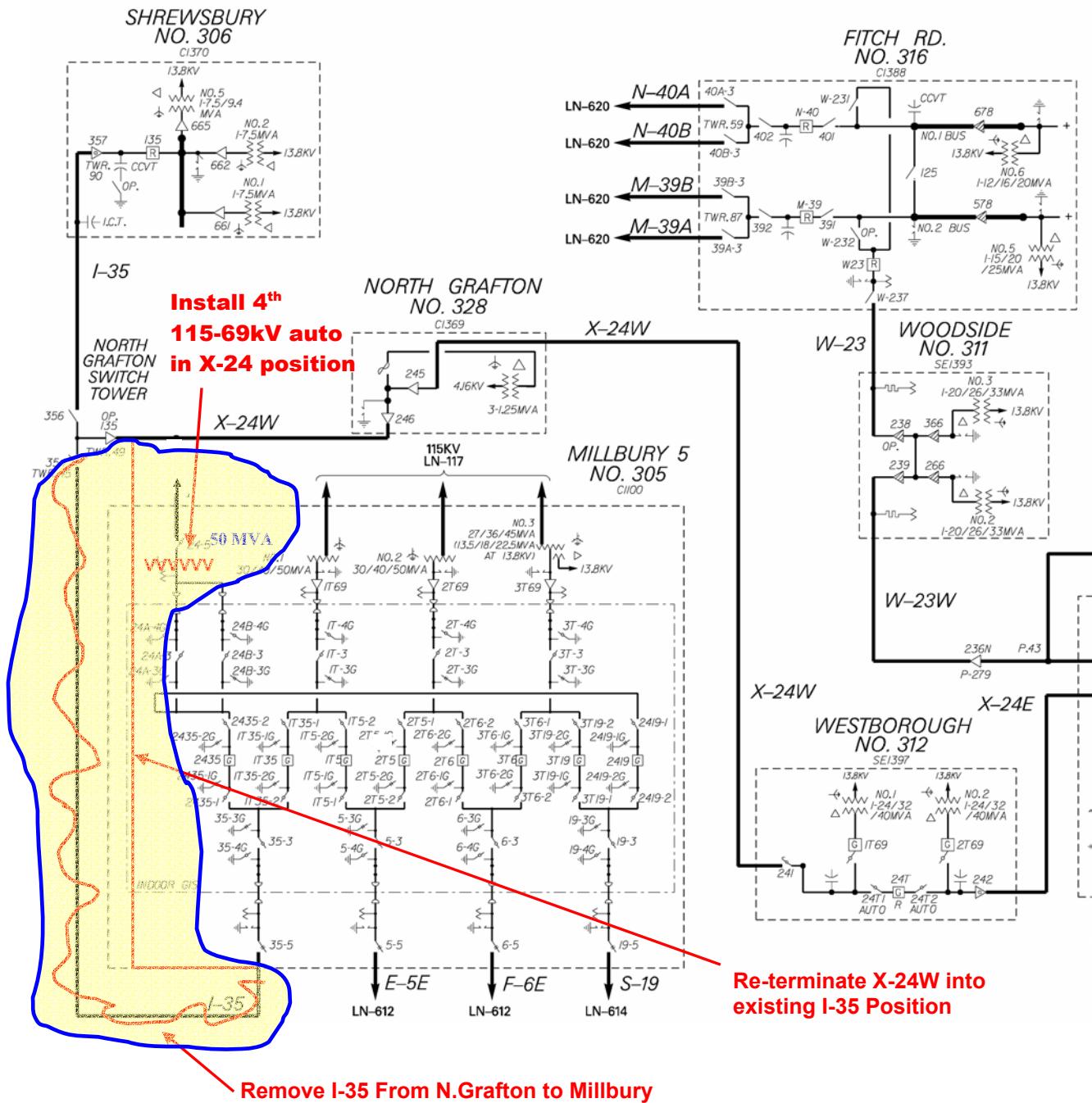
The following diagrams show the interconnection.

**Figure 9.2: Install 4<sup>th</sup> 115-69 kV Auto at Millbury: Tap Q-143**



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**Figure 9.3: Install 4<sup>th</sup> 115-69 kV Auto at Millbury: Remove I-35 & Re-Terminate X-24W**



## Study-Grade Cost Estimates

	Transmission Lines			Substation 4th Auto*	Totals
	Tap Q143	Remove I-35	Relocate XFMR Lines		
Capital:	\$230,000	\$0	\$7,000	\$1,450,000	\$1,687,000
O&M:	\$40,000	\$210,000	\$2,000	\$40,000	\$292,000
Removal:	\$45,000	\$25,000	\$1,000	\$10,000	\$81,000
<b>Total:</b>	<b>\$315,000</b>	<b>\$235,000</b>	<b>\$10,000</b>	<b>\$1,500,000</b>	<b>\$2,060,000</b>

# FINAL REPORT

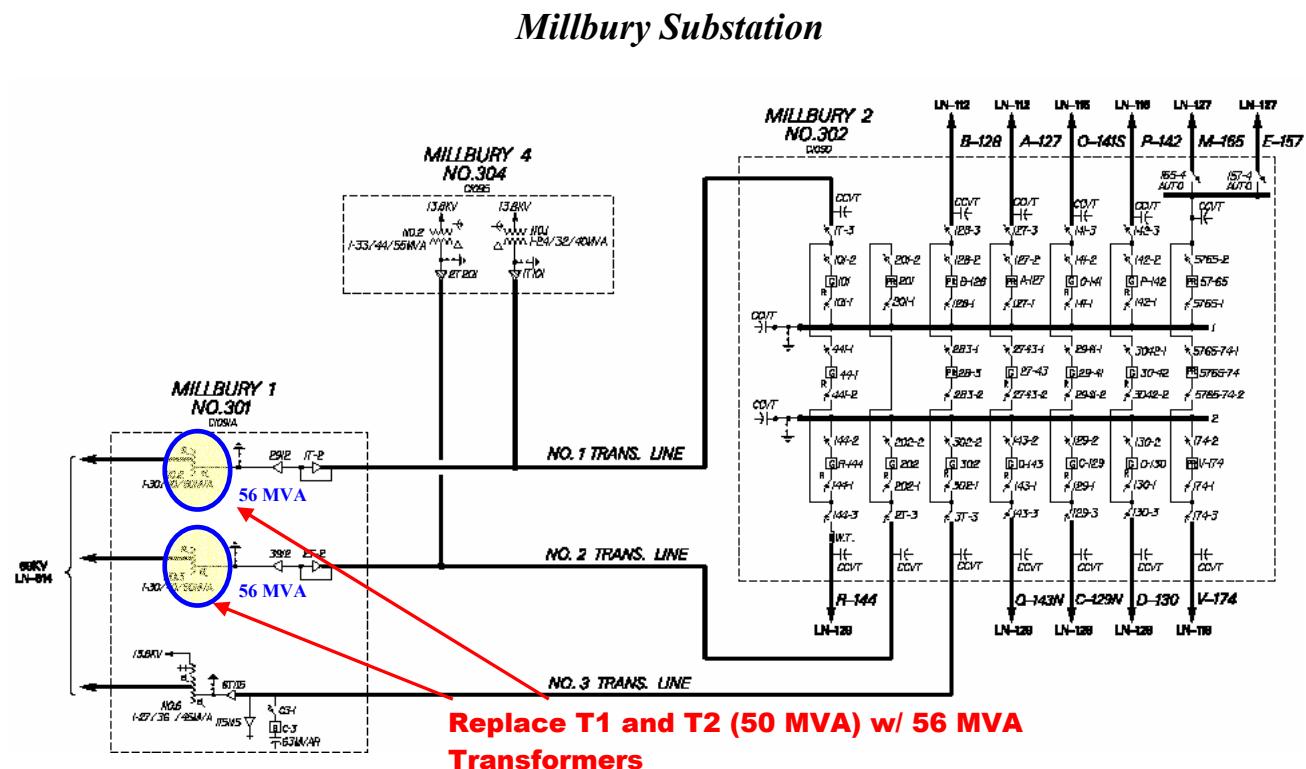
\* Utilizes existing 50 MVA spare at Millbury. Does not utilize existing X-24 cables for 4<sup>th</sup> autotransformer, due to infeasibility. Therefore, new cable must be purchased.

## 9.1.3 Replace Millbury T1 & T2 with 56 MVA Autotransformers

An alternative to installing a 4<sup>th</sup> 115-69 kV autotransformer at Millbury is to replace existing T1 and T2 (50 MVA transformers), with new 56 MVA transformers. Existing T1 and T2 not only have lower nameplate ratings (50 MVA) than the system standard (56 MVA), but also have much lower Summer Long-Time-Emergency (LTE) ratings. Existing T1 and T2 have Summer LTE ratings of 62 MVA, compared to system standard LTE of 84 MVA for new 115-69 kV transformers. Loadflow results indicate that an LTE rating 84 MVA for T1 and T2 will be sufficient for the time period up to 2015.

The following diagram illustrates the option.

**Figure 9.4: Replace Millbury T1 & T2 with 56 MVA Autotransformers**



## Study-Grade Cost Estimates

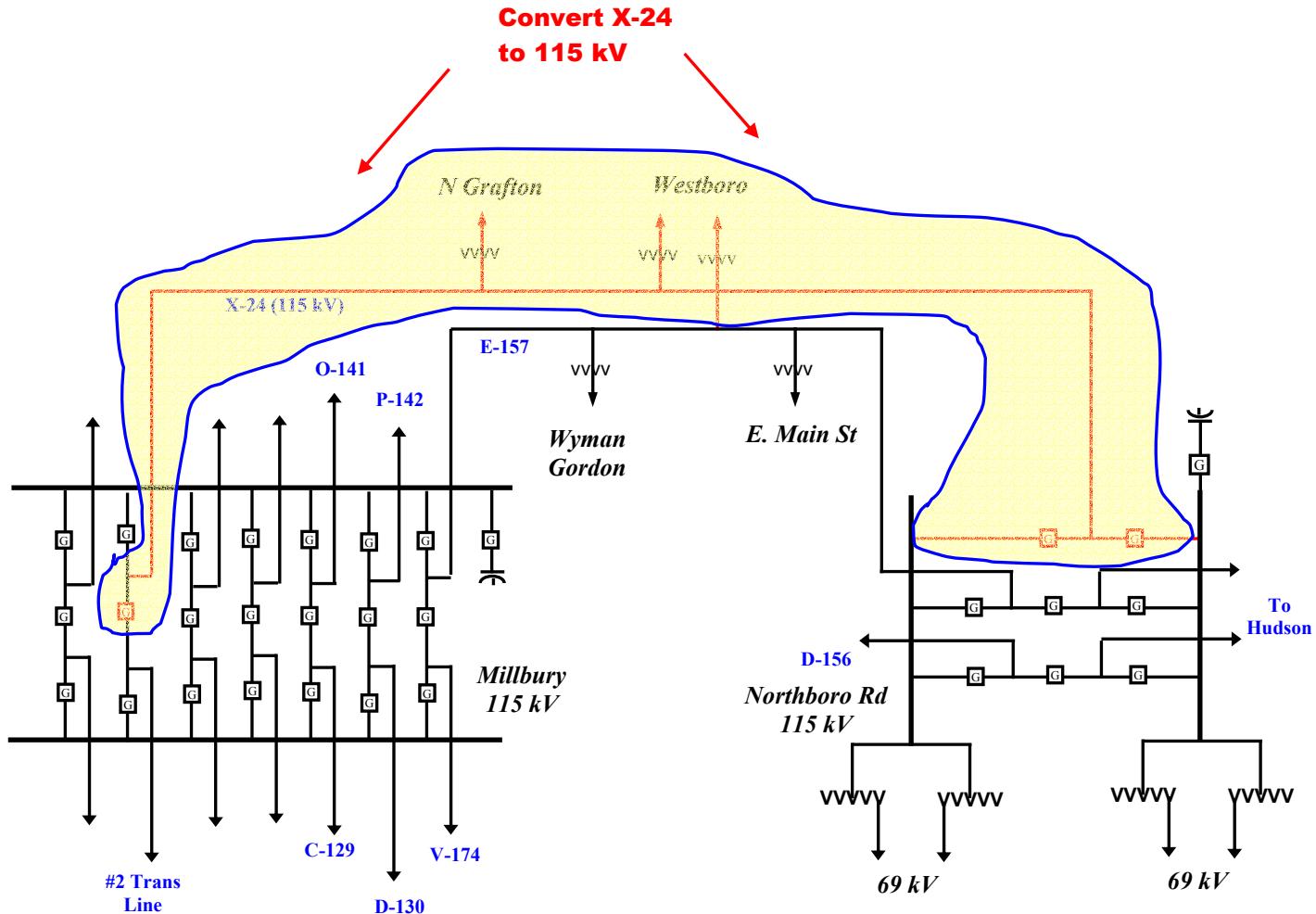
Millbury 115 kV Substation	Millbury 69 kV Substation	Transmission Line	Totals
Capital:	\$0	\$1,400,000	\$0 \$1,400,000
O&M:	\$0	\$ 25,000	\$0 \$ 25,000
Removal:	\$0	\$ 75,000	\$0 \$ 75,000
<b>Total:</b>	<b>\$0</b>	<b>\$1,500,000</b>	<b>\$0 \$1,500,000</b>

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## 9.1.4 Convert X-24 69 kV Circuit to 115 kV

The idea behind this option is to off-load the 115-69 kV transformers at Millbury by converting the X-24 69 kV line to 115 kV. X-24 is the most heavily loaded 69 kV line at Millbury. The plan is illustrated in the following diagram.

**Figure 9.5: Convert X-24 69 kV Circuit to 115 kV**



## Study-Grade Cost Estimates

	Northboro Rd Substation	Westboro Substation	N Grafton Substation	Millbury Substation	Transmission Line	Totals
Capital:	\$1,350,000	\$1,600,000	\$1,750,000	\$600,000	\$9,300,000	\$14,600,000
O&M:	\$ 0	\$ 0	\$ 0	\$ 0	\$ 0	\$ 0
Removal:	\$ 0	\$ 160,000	\$ 130,000	\$ 15,000	\$ 0	\$ 350,000
<b>Total:</b>	<b>\$1,350,000</b>	<b>\$1,760,000</b>	<b>\$1,880,000</b>	<b>\$615,000</b>	<b>\$9,300,000</b>	<b>\$14,950,000</b>

## 9.1.5 Recommendation

It is recommended that option 3 (Replace Millbury T1 & T2 with 56 MVA Autotransformers) be implemented to solve the subject problem, since option 3 is least cost (\$1.5 M).

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## 9.2 Alternatives Developed to Eliminate Overload of Ayer T4 & T6 (115-69 kV)

Study results indicate that the Ayer transformers (T4 and T6) overload for loss of each other during stressed system conditions. This is due to the heavy 69 kV load supplied radially from Ayer (e.g. Groton and Pepperell). To solve this problem, the following options were investigated:

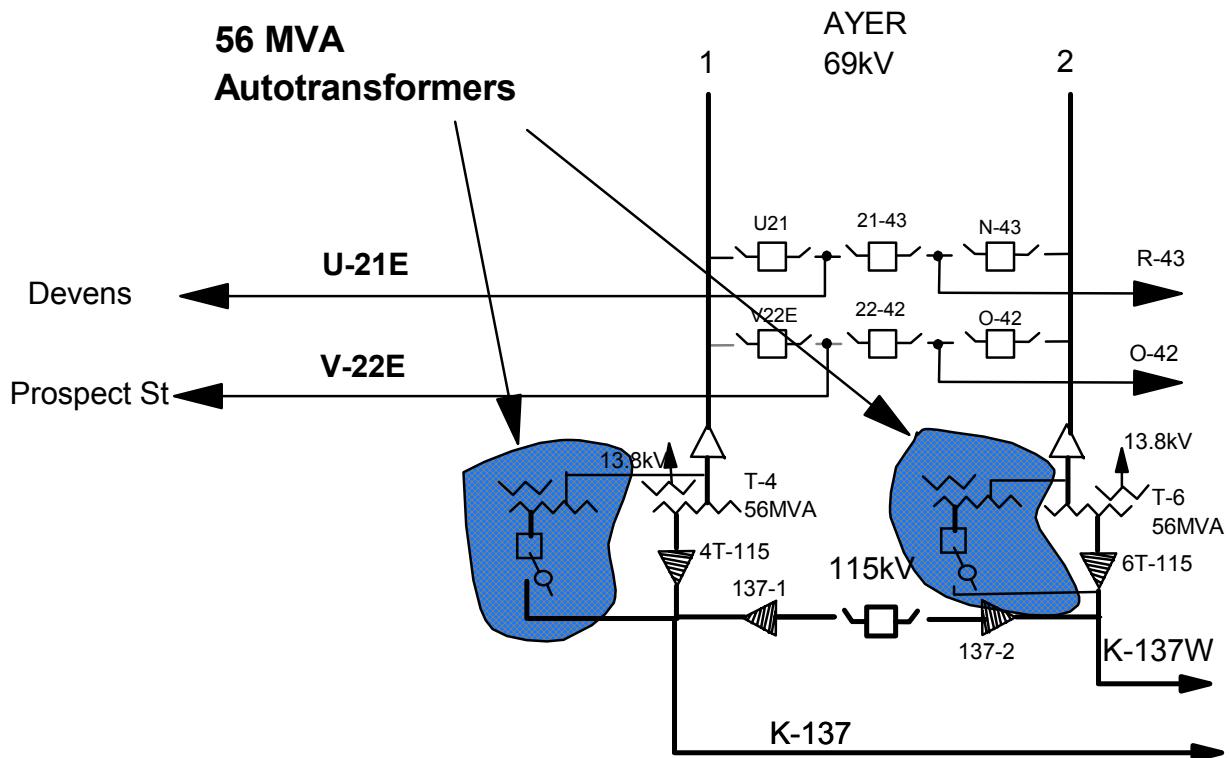
1. Install two additional 115-69 kV transformers at Ayer.
2. Off-load the 69 kV system at Ayer by transferring  $\frac{1}{2}$  of Prospect St load to Pratts Jct, and adding two 115-69 kV transformers at Pratts Jct.
3. Off-load the 69 kV system at Ayer by converting to V-22 69 kV line to 115 kV.

The following sections describe each option.

### 9.2.1 Install Two Additional 115-69 kV Transformers at Ayer

Installing two additional transformer at Ayer is practically very difficult due the existing substation layout. To make room for the two additional transformers, the control house will have to be torn down then rebuilt in another part of the substation. The diagram below shows the proposal:

Figure 9.6: Install Two Additional 115-69 kV Transformers at Ayer



#### Study-Grade Cost Estimates:

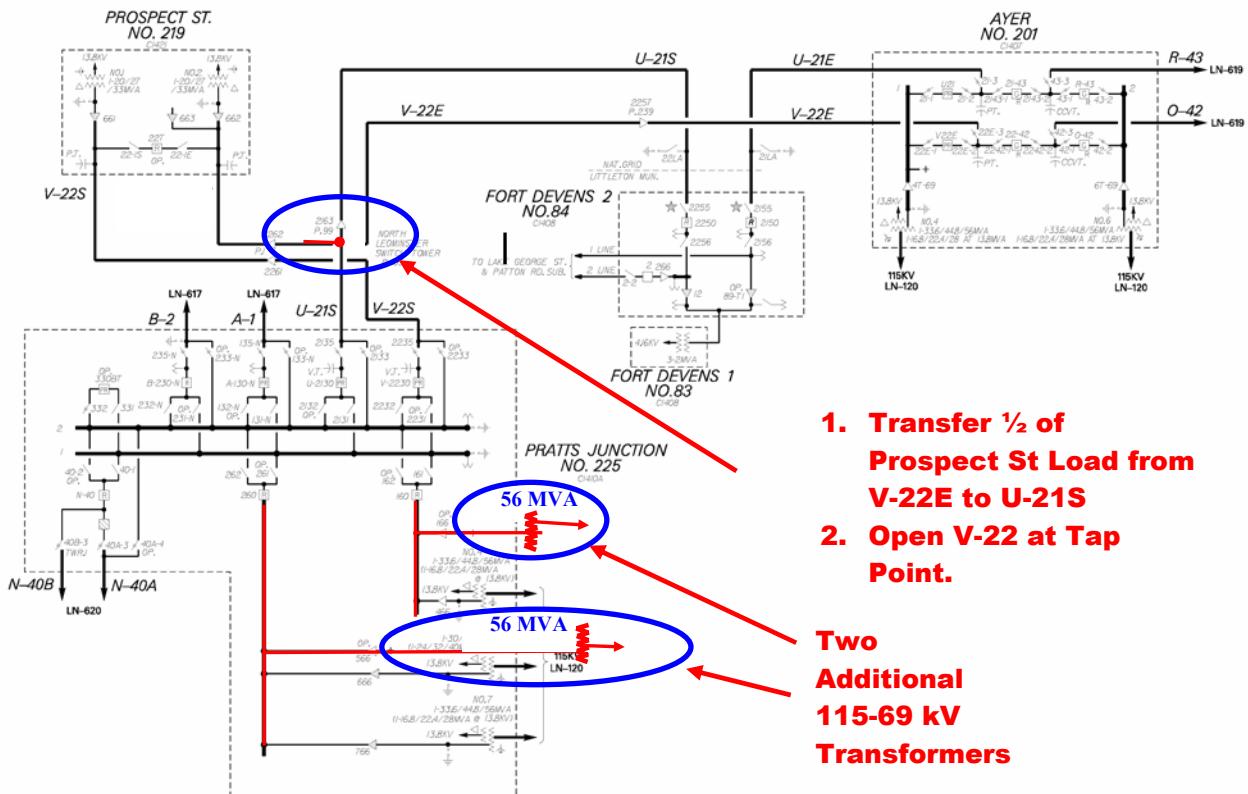
	Substation	Transmission Line	Totals
Capital:	\$4,350,000	\$ 0	\$4,350,000
O&M:	\$ 150,000	\$ 0	\$ 150,000
Removal:	\$ 50,000	\$ 0	\$ 50,000
Total:	<b>\$4,550,000</b>	<b>\$ 0</b>	<b>\$4,550,000</b>

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## 9.2.2 Transfer ½ Prospect St Load From V-22E to U-21S, Add Two 115-69 kV Autos at Pratts

This option entails transferring half of the Prospect St 69 kV load (currently served via the V-22E line from Ayer) to the U-21S line, which is served from Pratts Jct. This effectively off-loads T4 and T6 at Ayer, and transfers the load over to Pratts Jct. This transfer overloads existing 115-69 kV transformers at Pratts Jct (T6 and T4), thereby creating the need for two additional 115-69 kV autotransformers (56 MVA) at Pratts Jct. However, compared to adding transformation at Ayer, adding 115-69 kV transformers at Pratts Jct. is relatively easy. Five empty transformer bays are presently available at Pratts Jct. for the installation of additional 115-69 kV transformers. The diagram below shows the option.

**Figure 9.7: Transfer ½ Prospect St Load From V-22 to U-21 69 kV Line**



### Study-Grade Cost Estimates:

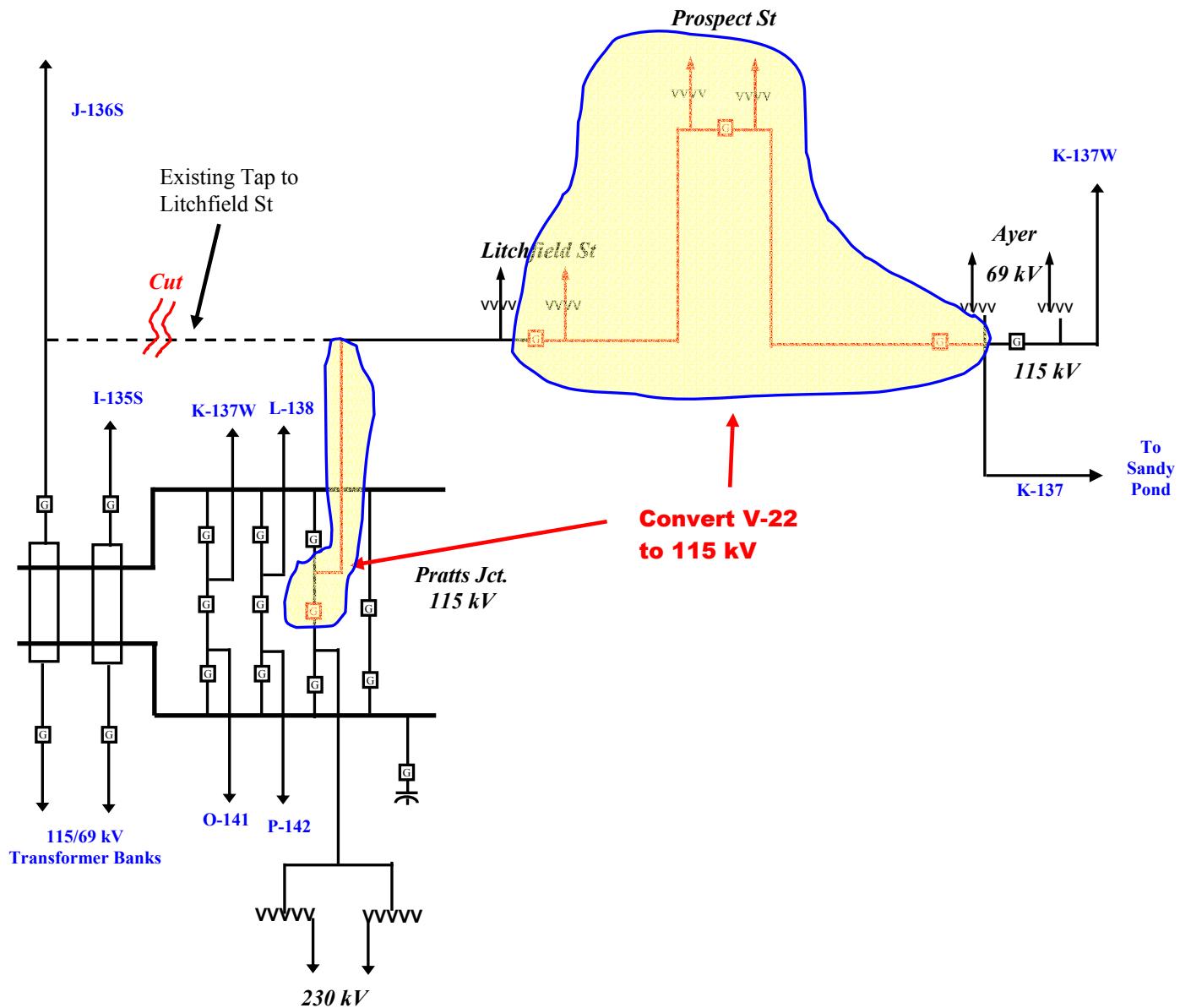
	Prospect St Substation	Pratts Jct. Substation	Transmission Line	Totals
Capital:	\$35,000	\$1,390,000	\$50,000	\$1,475,000
O&M:	\$ 0	\$ 5,000	\$ 0	\$5,000
Removal:	\$ 0	\$ 5,000	\$ 0	\$5,000
<b>Total:</b>	<b>\$35,000</b>	<b>\$1,400,000</b>	<b>\$50,000</b>	<b>\$1,485,000</b>

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## 9.2.3 Convert V-22 69 kV Circuit to 115 kV

The idea behind this option is to off-load the 115-69 kV transformers at Ayer by converting the V-22 69 kV line to 115 kV. Converting V-22 to 115 kV effectively eliminates the overload of T4 and T6 at Ayer. This option is illustrated in the following diagram.

**Figure 9.8: Convert V-22 69 kV Circuit to 115 kV**



### Study-Grade Cost Estimates

	Pratts Jct Substation	Litchfield St Substation	Prospect St Substation	Ayer Substation	Transmission Line	Totals
Capital:	\$340,000	\$1,900,000	\$2,500,000	\$1,650,000	\$7,000,000	\$13,390,000
O&M:	\$ 5,000	\$ 70,000	\$ 80,000	\$ 15,000	\$0	\$ 170,000
Removal:	\$ 5,000	\$ 30,000	\$ 35,000	\$ 30,000	\$0	\$ 100,000
<b>Total:</b>	<b>\$350,000</b>	<b>\$2,000,000</b>	<b>\$2,615,000</b>	<b>\$1,695,000</b>	<b>\$7,000,000</b>	<b>\$13,660,000</b>

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### **9.2.4 Recommendation**

It is recommended that Option 2 be implemented (Transfer  $\frac{1}{2}$  Prospect St Load From V-22E to U-21S, and add two 115-69 kV autotransformers at Pratts), since it is least cost.

### **9.3 Alternatives Developed to Eliminate Overload of Sandy Pond T1 & T2 (345-115 kV)**

Loadflow results indicate that the existing 345-115 kV transformers at Sandy Pond (T1 & T2) overload for certain contingencies during stressed system conditions.

To eliminate these overloads, three alternatives were developed. They are described below.

1. Install 2 new 345-115 kV Transformers (448 MVA) at Pratts Jct
2. Install 2 new 345-115 kV Transformers (448 MVA) at Wachusett
3. Install 2 new 345-115 kV Transformers (448 MVA) at Quinsigamond Jct

Each option is described in subsequent sections.

It should be noted that Tewksbury and Millbury were other locations considered for additional 345-115 kV transformation, but these locations were found not to eliminate the overload of Sandy Pond T1 and T2. A 3<sup>rd</sup> 345-115 kV autotransformer at Sandy Pond was also considered but was ruled out due to the following practical concerns.

1. Very difficult to implement, physically and electrically (most likely would require two new 345 kV autotransformers at Sandy Pond (2 in each bank).
2. Not desirable from a transmission system design standpoint - too much 345-115 kV transformation concentrated at one location (Sandy Pond).

#### **9.3.1 Pratts Jct - Install 2 new 345-115 kV Transformers (448 MVA)**

The existing Pratts Jct substation is very close to two 345 kV lines in the area (343 and 314). These lines connect the Sandy Pond and Millbury substations. Tapping these lines and connecting them to the Pratts Jct substation will require very little permitting.

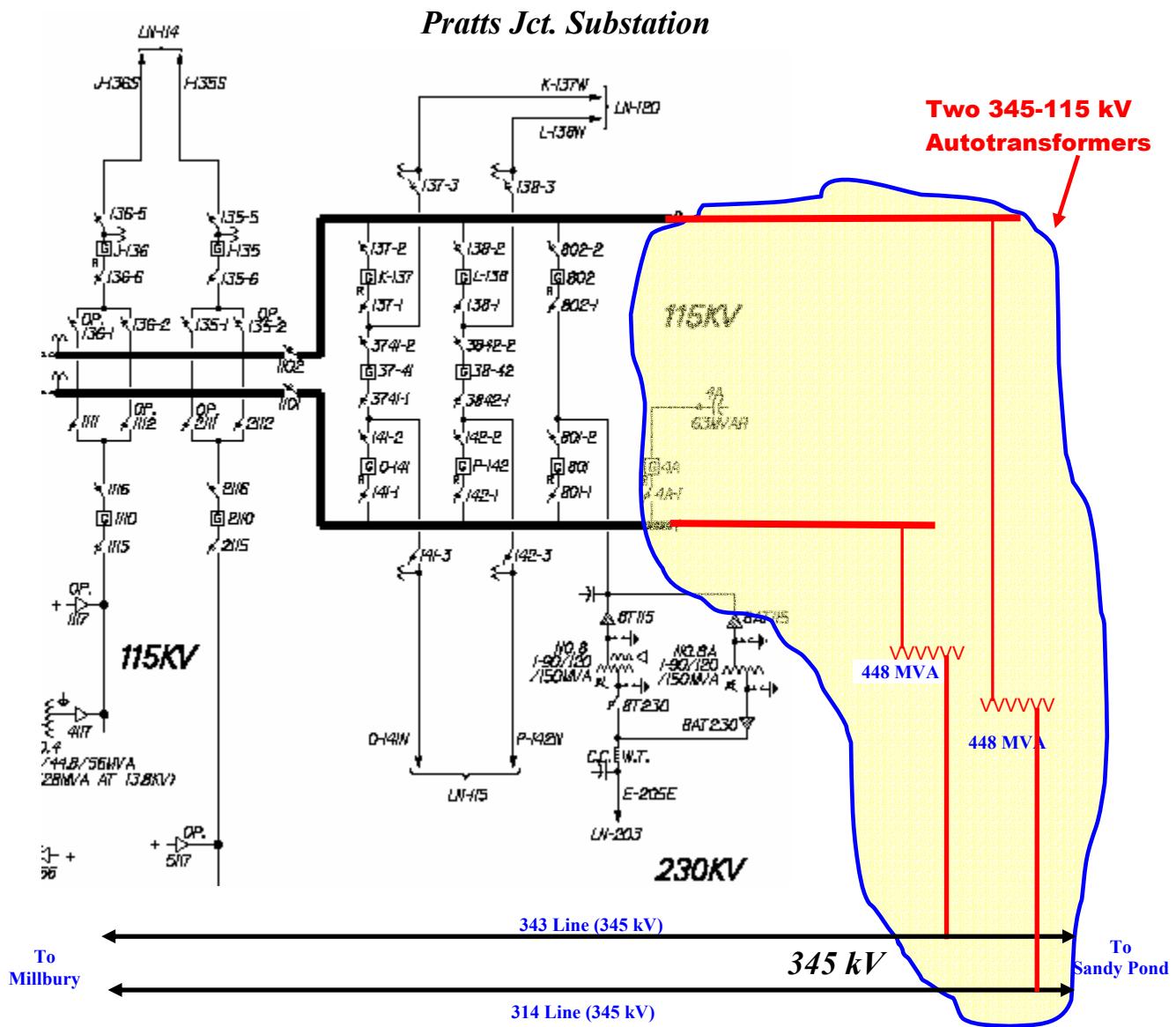
Note that one 345-115 kV autotransformer at Pratts Junction is not sufficient. With only one 345-115 kV transformer, loadflow results indicate that the K-137+L-138W Double Circuit Tower (DCT) contingency overloads the single 345-115 kV transformer during heavy load conditions. The K-137+L-138W DCT contingency essentially severs the 115 kV connection between Sandy Pond and the rest of the Central Massachusetts Transmission system, which leaves the single Pratts 345-115 kV transformer alone to supply most of the 115kV system by itself. Eliminating the K-137+L-138W DCT contingency (2.5 miles) is not feasible. Not enough room exists on the ROW to split the lines up onto two individual towers.

With two 345-115 kV autotransformers at Pratts Junction connected through a disconnect switch to lines 314 and 343, with no 345 kV breaker, loadflow results indicate that the overload of Sandy Pd T1 and T2 are effectively eliminated for the time period out to 2010.

The following one-line diagram shows the proposed interconnection of the 345-115 kV transformers at Pratt Jct.

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Figure 9.9: Two New 345-115 kV Autotransformers at Pratts Jct.



**Added Benefit – Eliminates 69 kV Voltage Problems in Ayer Area:** In addition to off-loading the existing Sandy Pond autotransformers, 345-115 kV transformation at Pratts Jct also eliminates all post-contingency (loss of K-137) voltage violations identified for the Ayer 69 kV area. This is because the 345-115 kV transformation at Pratts Jct provides a strong source on the west side of the Ayer substation. Presently, the

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only strong source into Ayer is from the east (K-137 line from Sandy Pond). Low voltage violations result following the loss of this line. With 345 kV transformation at Pratts, the K-137W line also becomes a strong source. Therefore, following loss of K-137, Ayer can be supplied via K-137W without experiencing any voltage violations.

### **9.3.1.1 Build 345 kV Ring Bus at Pratts Jct in 2010**

After 2010, lack of a 345 kV ring bus at Pratts Jct causes problems. First, the single Pratts 345-115 kV transformer that remains connected following the Millbury 1402 Breaker Failure contingency (314 + 301/302 + Carpenter Hill + Pratts 345 kV auto #1), overloads. Also, the Sandy Pond 337 BF contingency (Sandy Pond T2 + 337 + Sandy Pond T1<sup>2</sup>) overloads both Pratts Jct 345-115 kV autotransformers in 2012.

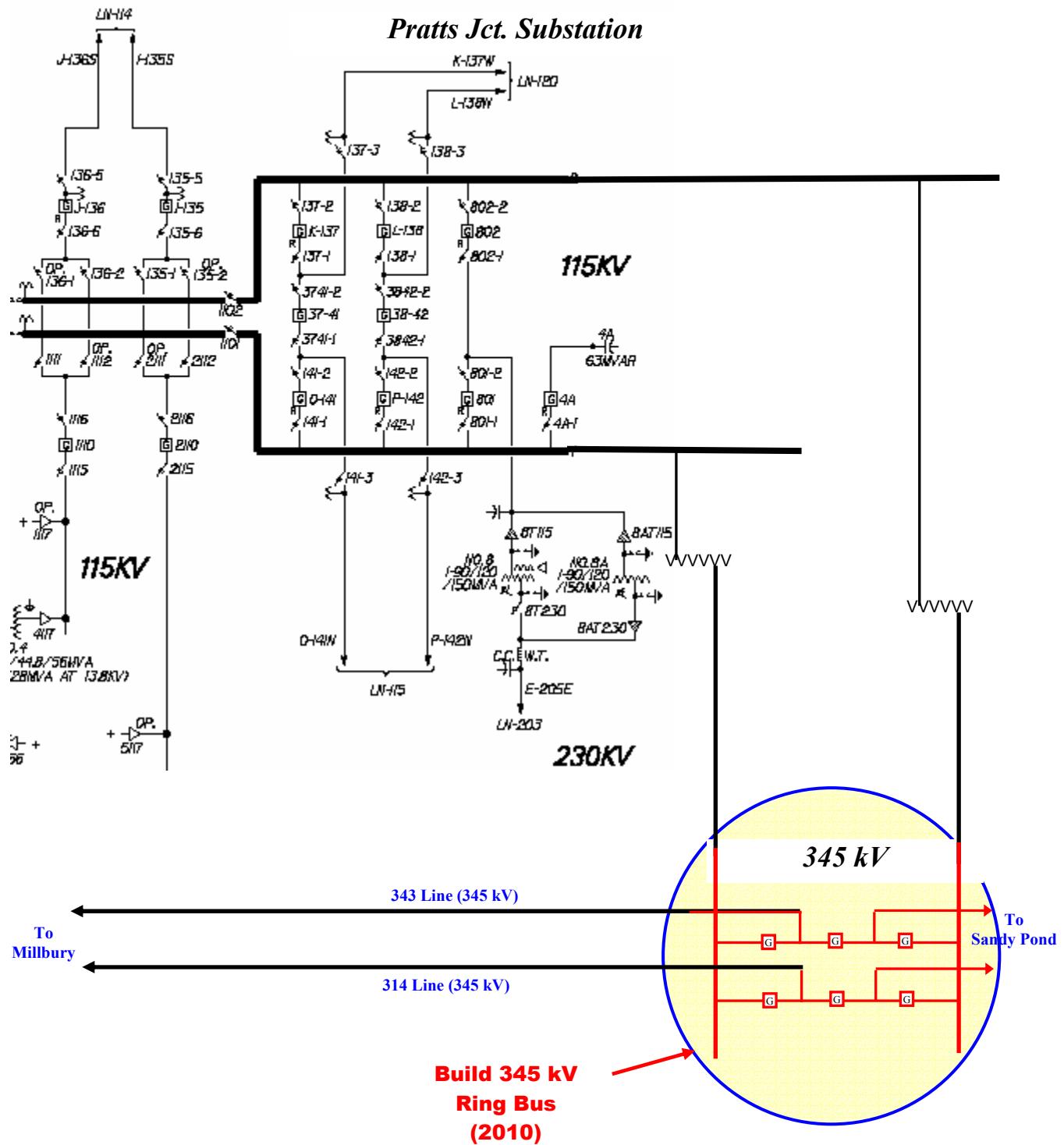
To eliminate these overloads, a 345 kV ring bus is proposed for Pratts Jct in year 2010. The following diagram illustrates the proposal.

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<sup>2</sup> Trip Sandy Pond T1 post-contingency since it will be overloaded during stressed system conditions

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**Figure 9.10: 345 kV Ring Bus at Pratts Jct.**



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## Study-Grade Cost Estimates:

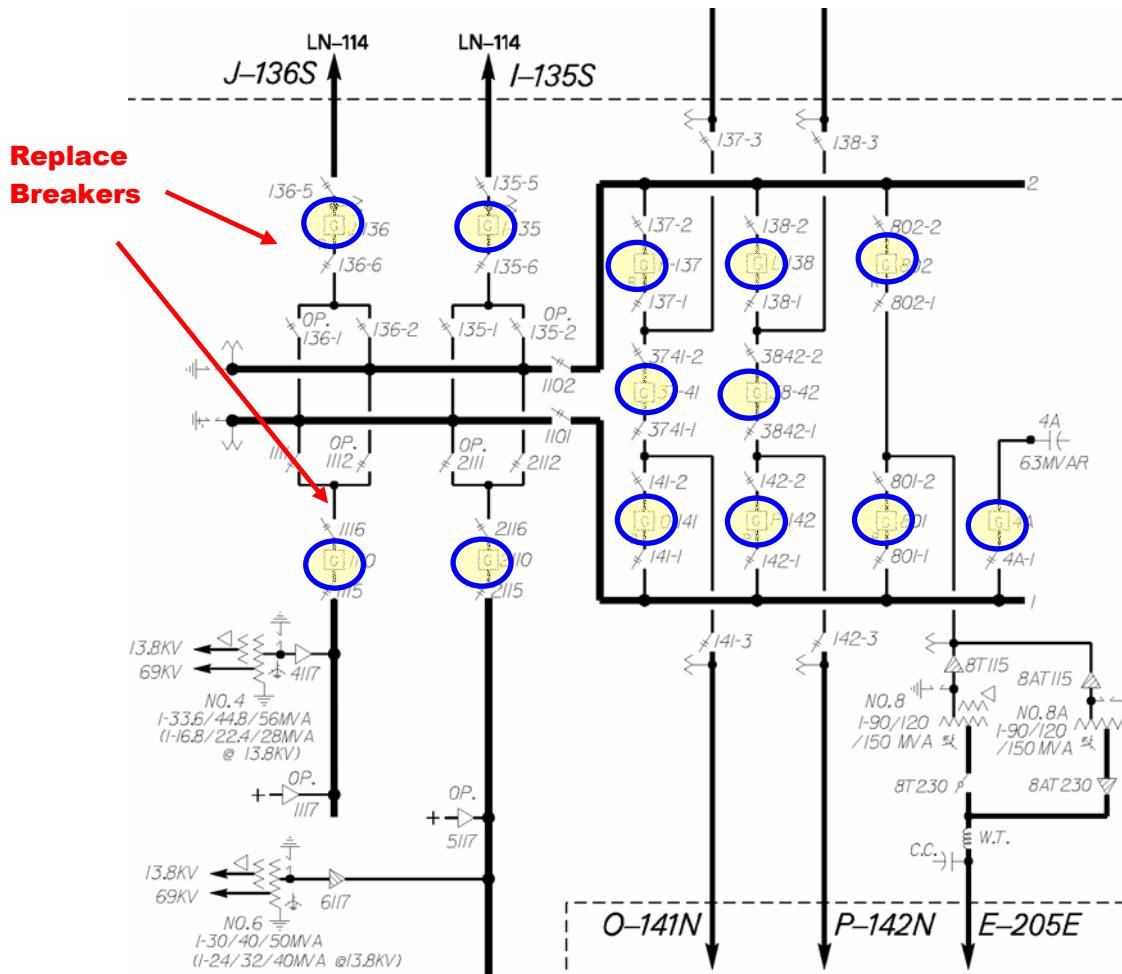
	Pratts Jct Substation	Transmission Line	Totals
Capital:	\$2,700,000	\$0.000	\$2,700,000
O&M:	\$0,000	\$0.000	\$0,000
Removal:	\$0,000	\$0.000	\$0,000
<b>Total:</b>	<b>\$2,700,000</b>	<b>\$0,000</b>	<b>\$2,700,000</b>

It should be noted that results of a Present Value (PV) analysis indicated that it was less costly to wait until year 2010 to install the 345 kV ring bus at Pratts Jct, as apposed to installing the ring bus with the 345-115 kV transformers.

### 9.3.1.2 Replace all Thirteen 115 kV Breakers at Pratts Jct

Study results indicate that, with the Pratts 345-115 kV transformers in-place, all thirteen 115 kV breakers at Pratts Jct need to be replaced due to excessive short-circuit duty. The following diagram shows the breakers that need to be replaced.

**Figure 9.11: Replace all Thirteen 115 kV Breakers at Pratts Jct**



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## Study-Grade Cost Estimates:

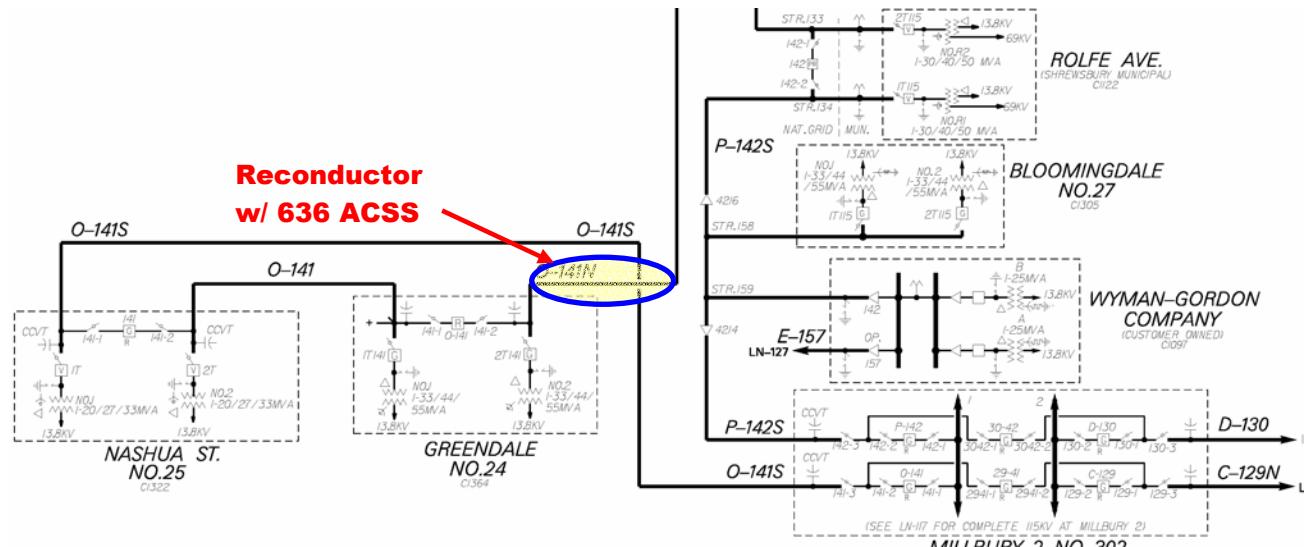
	Pratts Jct Substation	Transmission Line	Totals
Capital:	\$1,550,000	\$0.000	\$1,550,000
O&M:	\$65,000	\$0.000	\$65,000
Removal:	\$13,000	\$0.000	\$13,000
<b>Total:</b>	<b>\$1,628,000</b>	<b>\$0,000</b>	<b>\$1,628,000</b>

### 9.3.1.3 Reconduct O-141N [Quinsigamond Jct – Greendale] with 636 ACSS

Loadflow results indicate that, with the Pratts 345-115 kV transformers in-place, O-141N [Quinsigamond Jct – Greendale] overloads for several contingencies. The existing conductor size on O-141N between these two locations is 477 ACSR. To eliminate the overloads, this conductor size must be increased to at least 954, if using ACSR. An increase to 954 ACSR would require major structure upgrades along this section of O-141N, which would be very costly. An alternative to using ACSR is ACSS conductor. ACSS conductor has been used for many years in the former EUA system with satisfactory results. ACSS is lighter than ACSR and can be operated at higher temperatures (200C compared to 140C for ACSR). Calculations indicate that 636 ACSS, operating at maximum conductor temperature of 200C, provides sufficient thermal capability to eliminate all overloads on O-141N. Installing 636 ACSS on this section of O-141N will not require transmission structure upgrades, which provides significant cost savings over ACSR.

The following diagram shows the upgrade.

**Figure 9.12: Reconduct O-141N [Quinsigamond Jct – Greendale] with 636 ACSS**



## Study-Grade Cost Estimates:

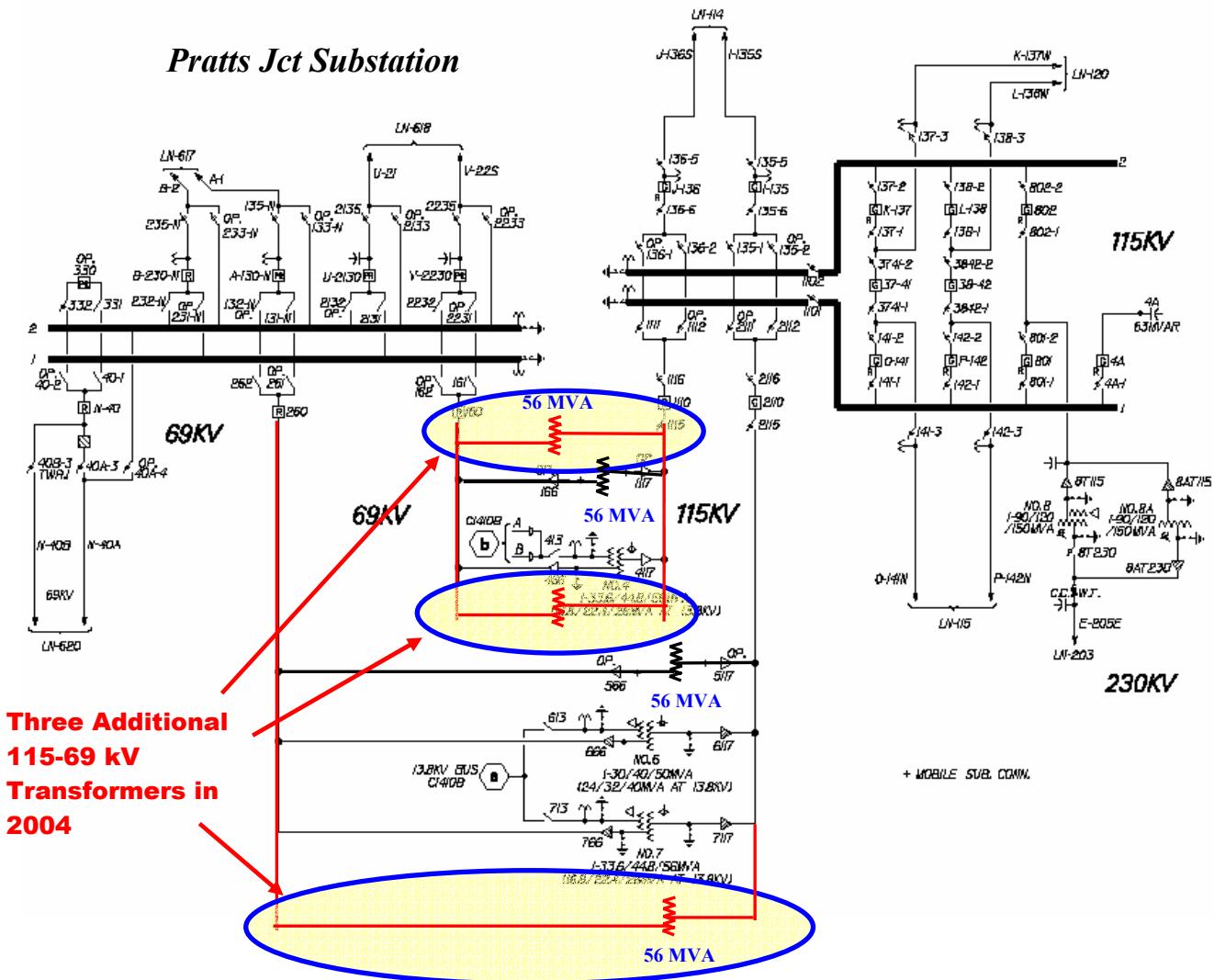
	Substation	Transmission Line	Totals
Capital:	\$0.0	\$550,000	\$550,000
O&M:	\$0.0	\$25,000	\$25,000
Removal:	\$0.0	\$175,000	\$175,000
<b>Total:</b>	<b>\$0.0</b>	<b>\$750,000</b>	<b>\$750,000</b>

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## 9.3.1.4 Install 3 Additional 115-69 kV Transformers at Pratts Jct (Total = 8)

Loadflow results indicate that, with the Pratts 345-115 kV transformers in-place, three additional 115-69 kV transformers at Pratts Jct (over and above the two proposed for the solution of the Ayer T4 and T6 overload problem) will be needed. All three are needed when the 345-115 kV transformers are installed. The following diagram shows the arrangement.

**Figure 9.13: Three Additional 115-69 kV Autotransformers at Pratts Jct. in 2004**



### Study-Grade Cost Estimates:

	Pratts Jct Substation	Transmission Line	Totals
Capital:	\$4,370,000	\$0.00	\$4,370,000
O&M:	\$20,000	\$0.00	\$20,000
Removal:	\$0	\$0.00	\$0
<b>Total:</b>	<b>\$4,390,000</b>	<b>\$0</b>	<b>\$4,390,000</b>

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**100 MVA Transformers Considered** – Instead of installing many new 56 MVA transformers (115-69 kV) at Pratts Jct, the option of migrating to 100 MVA transformers was considered. Use of 100 MVA transformers would decrease the number of transformers needed at Pratts Jct. However, 56 MVA is currently the National Grid standard size for 115-69 kV transformers. A 100 MVA spare would also have to be purchased. Moreover, a 100 MVA spare would be much more difficult to transport than the existing 56 MVA spare. Also, the existing mobile transformer for 115-69 kV is 50 MVA, which is the largest mobile size available in the industry. Migrating to 100 MVA therefore would preclude our ability to quickly replace 100 MVA transformers with a mobile. For these reasons, the option of migrating to 100 MVA transformers was rejected.

### 9.3.1.5 Convert N-40 & W-23 69 kV Circuits to 115 kV in 2012, Remove M-39 69 kV line

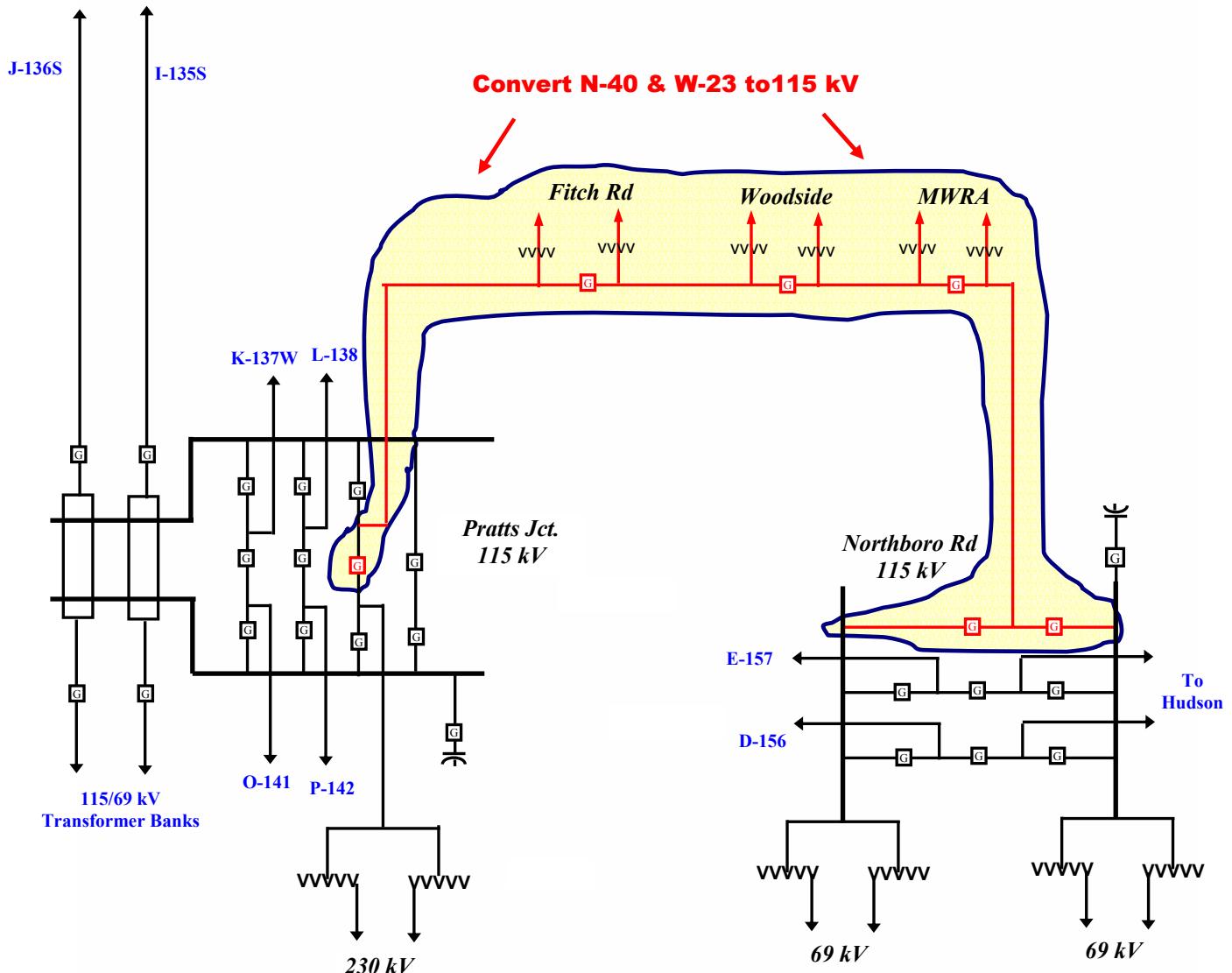
With two 345-115 kV autotransformers located at Pratts Jct, loadflow results indicate that two additional 115-69 kV transformers (over and above the 3 additional required in 2003, resulting in a total of 10, will be required at Pratts Jct by the year 2013. Although a sufficient amount of real-estate exists at the station for ten 115-69 kV transformers, installation of the 9<sup>th</sup> and 10<sup>th</sup> transformers will be quite difficult from an operational perspective. Moreover, a total of ten 56 MVA transformers at the station is rather excessive. Therefore, a total of eight 115-69 kV transformers is considered as the limit for Pratts Jct. No more can be added, from a system standpoint.

To eliminate this overload, load must be removed from the 69 kV transmission system near Pratts Jct. The most heavily loaded 69 kV line supplied from Pratts Jct is N-40. N-40 supplies power to both Fitch Rd substation, and the Northboro Rd area via the W-23 69 kV line. Due to the two 345-115 kV autotransformers located at Pratts Jct, a very high level of power tends to flow from Pratts Jct down to Northboro Rd via the N-40 and W-23 69 kV lines. If these lines were converted to 115 kV, loadflow results indicate that the overloads on the Pratts Jct 115-69 kV transformers would be eliminated.

This option (two 345 kV autotransformers at Pratts Jct) therefore requires the N-40 and W-23 to be converted to 115 kV in 2012. Note that, since the M-39 69 kV circuit [Fitch Rd – Wachusett] would no longer be of use, it would be removed. The following diagram illustrates the conversion.

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**Figure 9.14: Convert N-40 & W-23 69 kV Circuits to 115 kV**



## Study Grade Cost Estimates:

	Pratts Jct	Fitch Rd	Woodside	MWRA	Nboro Rd	M-39	N-40 Line	W-23 Line	Totals
	Substation	Substation	Substation	Substation	Substation	Removal			
Capital:	\$340,000	\$1,140,000	\$1,640,000	\$1,140,000	\$1,350,000	\$0	\$3,280,000	\$6,400,000	\$15,290,000
O&M:	\$5,000	\$0	\$0	\$0	\$0	\$0	\$205,000	\$400,000	\$610,000
Removal:	\$5,000	\$60,000	\$60,000	\$60,000	\$0	\$400,000	\$615,000	\$1,200,000	\$2,400,000
<b>Total:</b>	<b>\$350,000</b>	<b>\$1,200,000</b>	<b>\$1,700,000</b>	<b>\$1,200,000</b>	<b>\$1,350,000</b>	<b>\$400,000</b>	<b>\$4,100,000</b>	<b>\$8,000,000</b>	<b>\$18,300,000</b>

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### 9.3.1.6 If Can't Convert N-40 & W-23, Build new 345-115 kV Station near Millbury in 2012

Converting the N-40 and W-23 69 kV circuits to 115 kV will be very difficult and may not be feasible. The reasons for the difficulty are as follows:

1. National Grid does not own the W-23 line. The MDC, which owns this line, may not allow W-23 to be converted to 115 kV.
2. The W-23 ROW is very narrow, and traverses through neighborhoods in Northboro MA that are very residential. Since bigger towers will be needed for 115 kV operation, stiff public opposition may be encountered.
3. National Grid does not own a ROW for N-40. Rather, National Grid owns easements for this line, which means that National Grid may have to negotiate with every easement owner along the line.
4. Permitting may be difficult.

Due to aforementioned reasons, a fallback plan is needed if the W-23 and N-40 lines cannot be converted to 115 kV in 2012.

The reason the W-23 and N-40 lines need to be converted is to eliminate 115-69 kV transformer overloading at Pratts Jct. An alternative is to convert the V-22 69 kV to 115 kV. However, with V-22 converted, a large amount of power still tends to flow down N-40 and W-23 from Pratts Jct (strong source with 345 kV transformers installed) to Northboro Rd (weak source). Load flow simulations indicate that the post-contingency flow on W-23 and N-40 can exceed 13 and 18 times Surge Impedance Loading (SIL), respectively. This results in large VAr losses across these lines that in turn result in low voltages in the Northboro Rd Area. Therefore, converting any other 69 kV line emanating from Pratts to 115 kV, besides N-40, is considered unviable with respect to solving the 115-69 kV transformer overload problem at Pratts Jct.

The only viable fallback option that was developed, was the creation of a stronger source in the Millbury area, that would electrically “push back” the flow on the N-40 and W-23 lines, thereby off-loading the 115-69 kV transformers at Pratts Jct. The creation of this source requires a new 345-115 kV substation in the Millbury area. Loadflow results indicate that the existing Millbury substation is not a good location for 345-115 kV transformation even with two 345-115 kV transformers at Pratts, since two 345-115 kV transformers (448 MVA) would not be enough. Simulations show that loss of one Millbury transformer would overload the remaining transformer. In addition, the installation of two 345-115 kV transformers at Millbury would over-duty every 115 kV breaker in the station.

An alternative location for a 345-115 kV substation in the Millbury area is a parcel of land near Wyman Gordan. This location is electrically far enough away from Millbury such that two 345-115 kV transformers do not cause short-circuit problems, or overload for loss of each other. At the same time, Wyman Gordan is closer to Northboro Rd than Millbury is, and therefore would provide greater voltage support for Northboro Rd. Loadflow simulations indicate that a 345-115 kV substation near Wyman Gordon, tapped into the E-157 line, would effectively eliminate the overload of the Pratts Jct 115-69 kV transformers by reducing the flow on W-23 and N-40 from Pratts Jct to Northboro Rd. However, although open land is available near the site, it is by no means certain that this land will be available for purchase in 2012.

Although the Wyman Gordan site may not be available, loadflow results indicate that other sites in the Millbury area would also be suitable to solve the 115-69 kV transformer overload problem at Pratts Jct. Therefore, a new 345-115 kV substation, located somewhere near the existing Millbury substation, is considered a viable fallback option for this study. Note that preliminary loadflow simulations indicate that a 345-115 kV substation at Wyman Gordon would overload the existing E-157 115 kV line [Wyman Gordon – Northboro Rd (10.5 mi)]. The existing E-157 conductor is 795 ACSR. To eliminate this overload, at least 1113 ACSR must be installed. Also, the O-141S/P-142S 115 kV terminal equipment at Millbury would become overloaded.

No cost-estimate was developed for this fallback option. For the new substation, the cost estimate recently developed for a new 345-115 kV Quisigimond Jct (two 345-115kV autotransformers (448 MVA) with three 115 kV breaker bays, no 345 kV breakers) was deemed an adequate surrogate. The cost estimates follow.

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### **Study-Grade Cost Estimates:**

	<b>Wyman Gordon</b>	<b>Reconductor E-157**</b>	<b>Upgrade O-141S/P-142S</b>	<b>Totals</b>
	<b>Substation</b>	<b>Transmission Line</b>	<b>Transmission Line</b>	
Capital*:	\$23,200,000	\$2,200,000	\$1,600,000	\$490,000
O&M:	\$0,000	\$0	\$0,000	\$0,000
Removal:	\$0,000	\$0	\$0,000	\$10,000
<b>Total:</b>	<b>\$23,200,000</b>	<b>\$2,200,000</b>	<b>\$1,600,000</b>	<b>\$27,490,000</b>

\*Includes \$1.5M to purchase land needed for new substation.

\*\* \$150,000/mile reconductoring cost assumed.

### **9.3.2 Wachusett - Install 2 new 345-115 kV Transformers (448 MVA)**

The second option investigated to eliminate the overload of Sandy Pd T1 and T2 was the addition of two new 345-115 kV autotransformers at Wachusett Station in W Boylston MA. The existing Wachusett substation is adjacent to the 314 and 343 lines (345 kV) between Sandy Pond and Millbury substations.

Note that, like the Pratts 345 kV option, one 345-115 kV autotransformer (448 MVA nameplate) at Wachusett is not sufficient. Since with only one 345-115 kV transformer, loadflow results indicate that the K-137+L-138W Double Circuit Tower (DCT) contingency overloads the single 345-115 kV transformer during heavy load conditions as early as 2006. Also, the 301/302 345 kV contingency overloads a single Wachusett 345-115 kV transformer in 2008. Therefore, two 345-115 kV autotransformers at Wachusett are required.

With two 345-115 kV autotransformers at Wachusett connected to lines 314 and 343 through a disconnect switch, with no 345 kV breaker, loadflow results indicate that the overload of Sandy Pd T1 and T2 are effectively eliminated for the time period out to 2008.

### **345 kV Ring Bus:**

Loadflow indicates that a 345 kV ring bus is needed at Wachusett. There are a few reasons for this. First, without a 345 kV ring bus at Wachusett, the Sandy Pd 343 BF contingency takes out Sandy Pd T2 along with a Wachusett 345 auto. Following this contingency, Sandy Pd T1 overloads as early as year 2006. Although an automatic isolation scheme exists at Sandy Pd, which isolates a failed breaker approximately 5 seconds after its failure, this scheme could fail. If the scheme fails, the Sandy Pd 343 BF contingency could have unacceptable inter-area impact, since Sandy Pd T1 (overloaded) would have to be manually tripped. Tripping Sandy Pd T1 would then overload the remaining Wachusett 345 kV auto, which would then have to be tripped. With no 345 kV autos at either Sandy Pd or Wachusett, 345 kV autos in the Boston area would overload (i.e. Woburn).

Note that, if failure of the automatic isolation scheme was not found to result in an unacceptable inter-area impact, and the post contingency loading on any element was found not to exceed its STE rating, a 345 kV ring bus may not have been necessary. However, this was not the case.

Second, with no 345 kV ring bus at Wachusett, the single Wachusett 345-115 kV transformer that remains in-service following the Millbury 1402 Breaker Failure contingency (314 + 301/302 + Carpenter Hill + Wachusett 345 kV auto #1), overloads in 2008.

### **Use of Existing Millbury T1 & T2 at Wachusett**

Loadflow results indicate that, with the Wachusett 345-115 kV transformers in-place, two additional 115-69 kV transformers need to be installed due to the thermal overload of existing 115-69 kV transformation at Wachusett. This will result in a total of four 115-69 kV transformers at Wachusett substation. Results also

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indicate that the existing T1 and T2 115-69 kV autotransformers at Millbury, already recommended to be replaced with larger transformers, provide sufficient thermal capability at Wachusett until at least 2015. Utilizing existing Millbury T1 and T2 at Wachusett will eliminate the need to by two additional 115-69 kV transformers, resulting in a total cost savings of \$850k.

Note that the addition of only one 115-69 kV transformer at Wachusett (instead of two) was also considered. However, breaker failure contingencies at Wachusett reduce the viability of this option, since, wherever a 3rd transformer is installed, a breaker failure contingency (either on the 115 kV or 69 kV) would take out two 115-69 kV transformers, which would overload the remaining transformer. For example, if a 3rd transformer was hung off any one of the 115 kV lines, a 115 kV Breaker Failure would take two transformers with it. Also, any 69 kV breaker failure would take two autotransformers with it. Moreover, it a 3rd transformer would require an additional 69 kV breaker, which would make this option more costly than the option proposed (two existing 115-69 kV autos from Millbury).

**Protection Issue** - Note that existing T1 and T2 at Millbury do not have tertiary windings, while the existing 115-69 kV transformer at Wachusett (T2) does have tertiary windings. The second Wachusett 115-69 kV transformer, planned for 2003, also will have tertiary windings. Based on a review by Protection Engineering, this difference should not cause relay coordination problems, as long as one of the Millbury autotransformers is not operating by itself in a dedicated breaker position. In other words, following failure of one of the transformers with tertiary windings, the remaining transformer without tertiary windings (i.e. Millbury T1 or T2) can't be placed back in-service by itself. Loadflow results indicate that this operating mode will not cause thermal or voltage problems.

### **69 kV Short-Circuit Duty at Wachusett**

Short-circuit simulation results indicate that, with the Wachusett 345-115 kV transformers in-place, all five 69 kV breakers need to be replaced due to excessive short-circuit duty.

### **Added Benefit – Eliminates 69 kV Voltage Problems in Ayer Area**

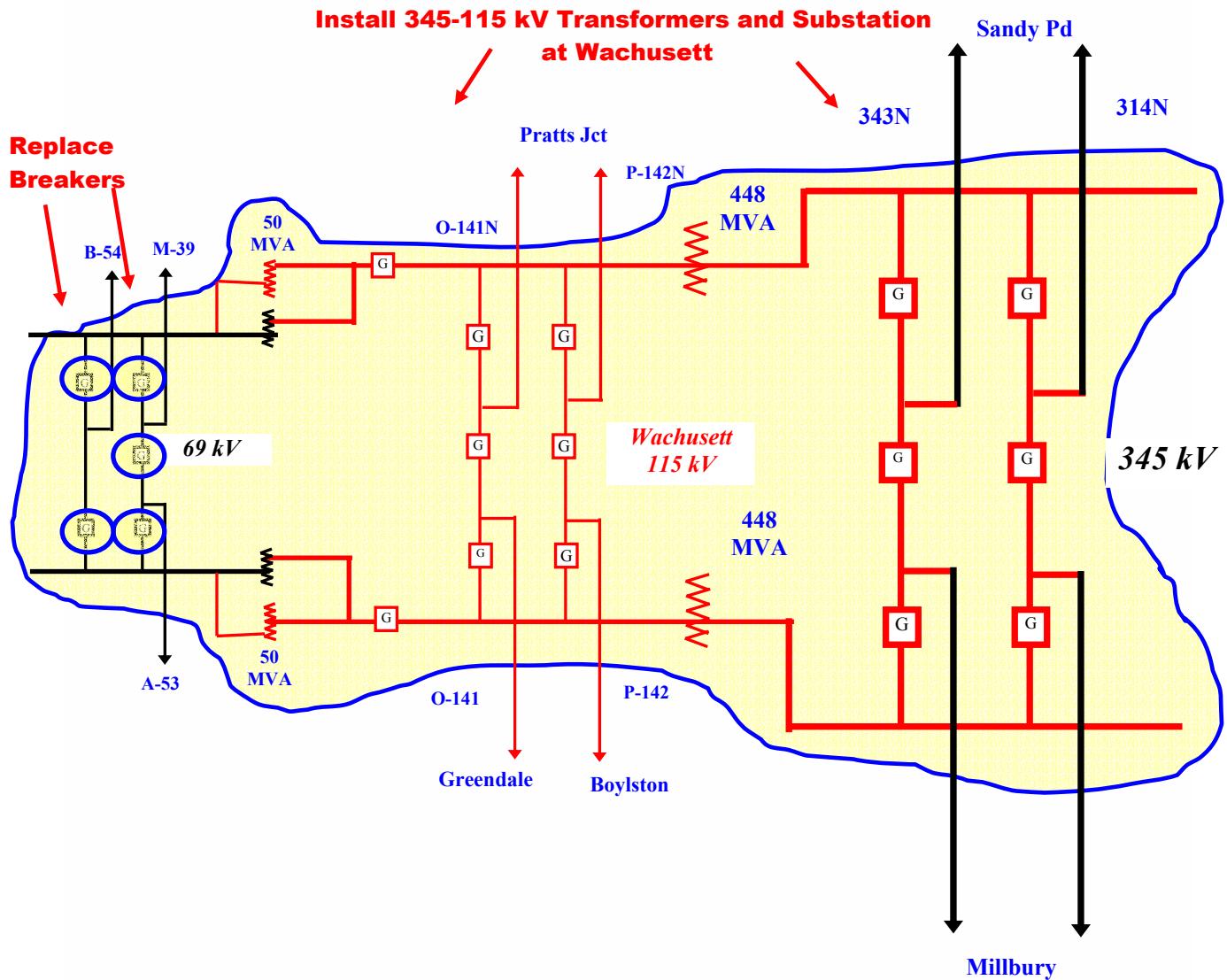
Like the Pratts Option (Option 1), 345-115 kV transformation at Wachusett also eliminates all post-contingency voltage violations (resulting from loss of K-137) identified for the Ayer 69 kV area.

### **One-Line Diagram**

The following one-line diagram shows the proposed interconnection of the 345-115 kV transformers at Pratt Jct, including the new 345/115 kV substation, and also 69 kV additions.

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Figure 9.15: 2 New 345-115 kV Transformers at Wachusett



## Study-Grade Cost Estimates:

Wachusett Substation		Savings Realized from use of Millbury T1 and T2 @ Wachusett	Transmission Line	Totals
345/115/69 kV*	345 kV Ring**			
Capital:	\$22,500,000	\$3,000,000	(\$850,000)	\$25,400,000
O&M:	\$250,000	\$50,000	\$0	\$0
Removal:	\$50,000	\$0	\$0	\$50,000
Total:	\$22,800,000	\$3,050,000	(\$850,000)	\$25,750,000

\*Includes two 345 kV breakers

\*\*Completes 345 kV ring with 4 additional 345 kV Breakers

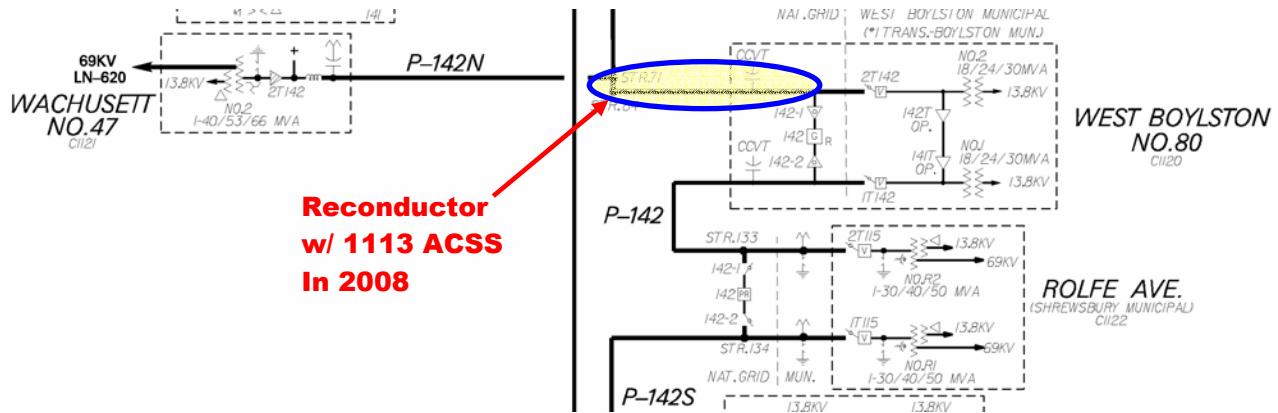
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## 9.3.2.2 Recondutor P-142N [Wachusett – Boylston] with 1113 ACSS in 2008

After 2008, loadflow results indicate that, with the Wachusett 345-115 kV transformers in-place, P-142N between Wachusett and Boylston overloads for several contingencies. The existing conductor size on this transmission line is 954 ACSR. To eliminate the overloads, this conductor size must be increased to at least 1113 ACSR. However, to increase transmission system robustness, the 1351 ACSS can be installed without major tower upgrades. The cost of 1113 ACSS is only \$50k more (i.e. 40% more) than 1113 ACSR. Therefore, 1113 ACSS is recommended.

The following diagram shows the upgrade.

**Figure 9.16: Recondutor P-142N [Wachusett – Boylston] with 1113 ACSS in 2008**



### Study-Grade Cost Estimates:

Substation	Transmission Line	Totals
Capital:	\$0	\$150,000
O&M:	\$0	\$6,000
Removal:	\$0	\$19,000
<b>Total:</b>	<b>\$0</b>	<b>\$175,000</b>

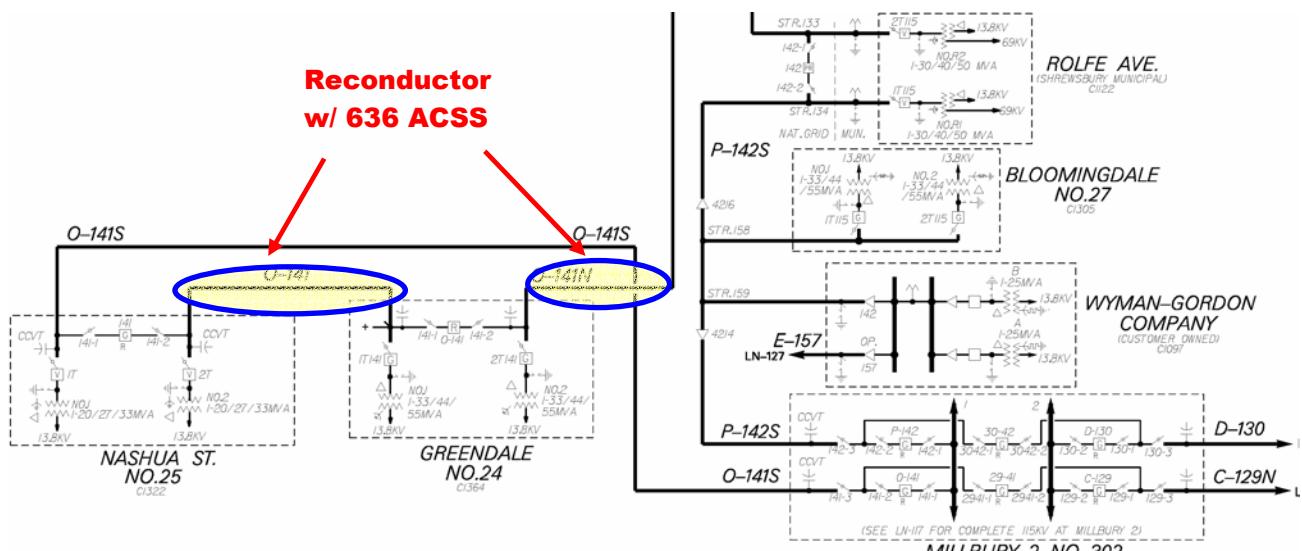
## 9.3.2.3 Recondutor O-141N [Quinsigamond Jct – Greendale - Nashua St] with 636 ACSS

Loadflow results indicate that, with the Wachusett 345-115 kV transformers in-place, O-141N sections [Quinsigamond Jct – Greendale – Nashua St] overload for several contingencies. The existing conductor size on O-141N between these two locations is 477 ACSR. To eliminate the overloads, this conductor size must be increased to at least 954, if using ACSR. An increase to 954 ACSR would require major structure upgrades along this section of O-141N, which would be very costly. An alternative to using ACSR is ACSS conductor. ACSS conductor has been used for many years in the former EUA system with satisfactory results. ACSS is lighter than ACSR and can be operated at higher temperatures (200C compared to 140C for ACSR). Calculations indicate that 636 ACSS, operating at maximum conductor temperature of 200C, provides sufficient thermal capability to eliminate all overloads on O-141N between Quinsigamond Jct and Nashua St substation. Installing 636 ACSS on this section of O-141N will require minor transmission structure upgrades, and provide significant cost savings over ACSR.

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The following diagram shows the upgrade.

**Figure 9.17: Recondutor O-141N [Quinsigamond Jct – Greendale – Nashua St] with ACSS**



## Study-Grade Cost Estimates:

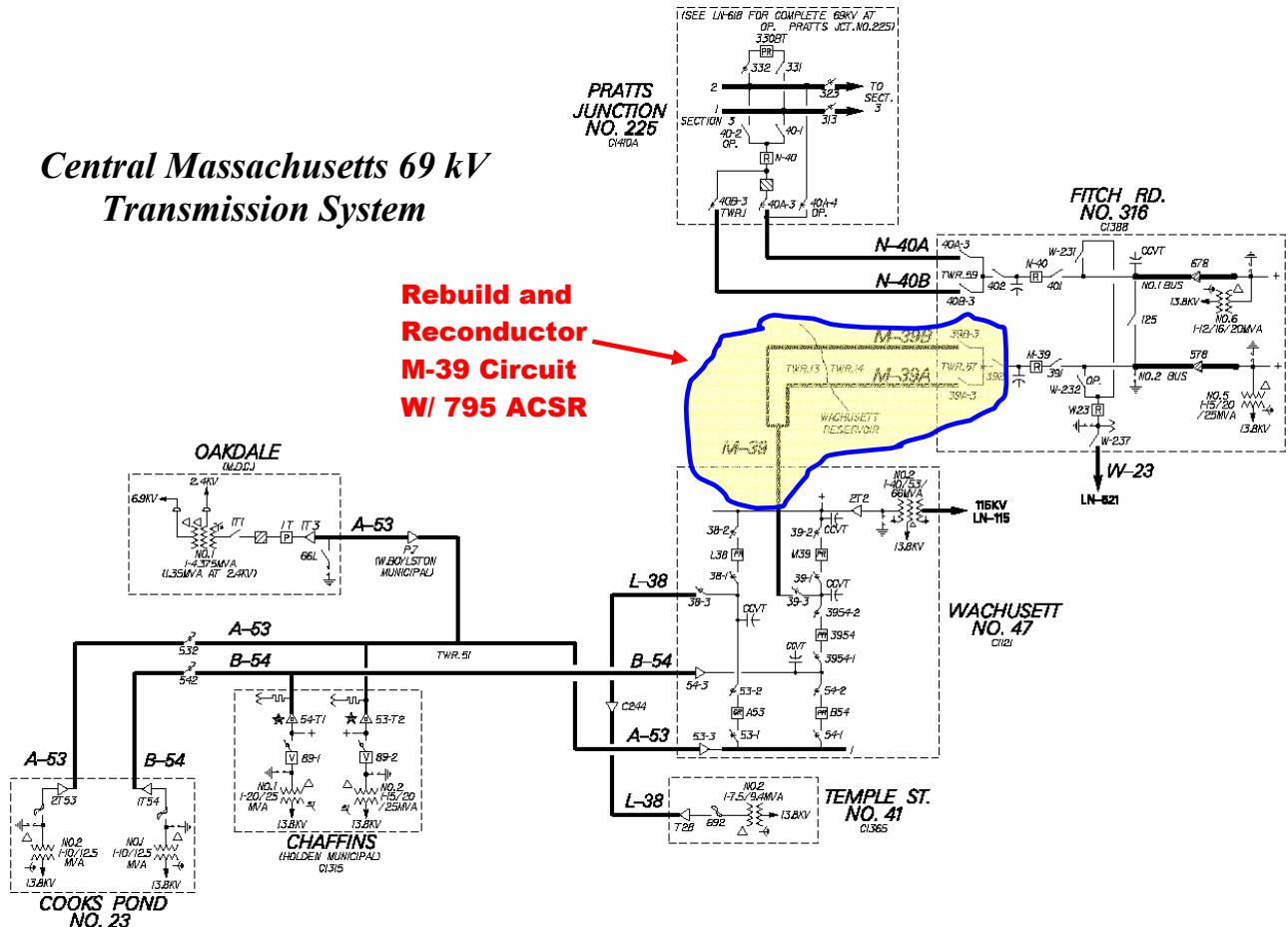
Substation	Transmission Line		Totals
	Recondutor O-141 (636 ACSS)	Recondutor O-141N (636 ACSS)	
Capital:	\$0.0	\$550,000	\$550,000 \$1,100,000
O&M:	\$0.0	\$25,000	\$25,000 \$50,000
Removal:	\$0.0	\$175,000	\$175,000 \$350,000
Total:	\$0.0	\$750,000	\$750,000 \$1,500,000

### 9.3.2.4 Recondutor M-39 69 kV line w/ 795 ACSR

Adding 345 kV autotransformers at Wachusett, causes the existing M-39 69 kV circuit to overload for certain contingencies. Load flow results indicate that the circuit rating of M-39 should be increased to at least 170 MVA. This requires that M-39 be totally rebuilt. 6' triangular structures will be used. No terminal equipment upgrades will be required. The following diagram shows the proposed upgrade.

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**Figure 9.18: Reconstructor M-39 69 kV Circuit w/ 795 ACSR**



## Study-Grade Cost Estimates:

	Stations	Lines	Totals
Capital:	\$170,000	\$1,000,000	\$1,170,000
O&M:	\$ 5,000	\$0	\$ 5,000
Removal:	\$ 5,000	\$0	\$ 5,000
<b>Totals:</b>	<b>\$180,000</b>	<b>\$1,000,000</b>	<b>\$1,180,000</b>

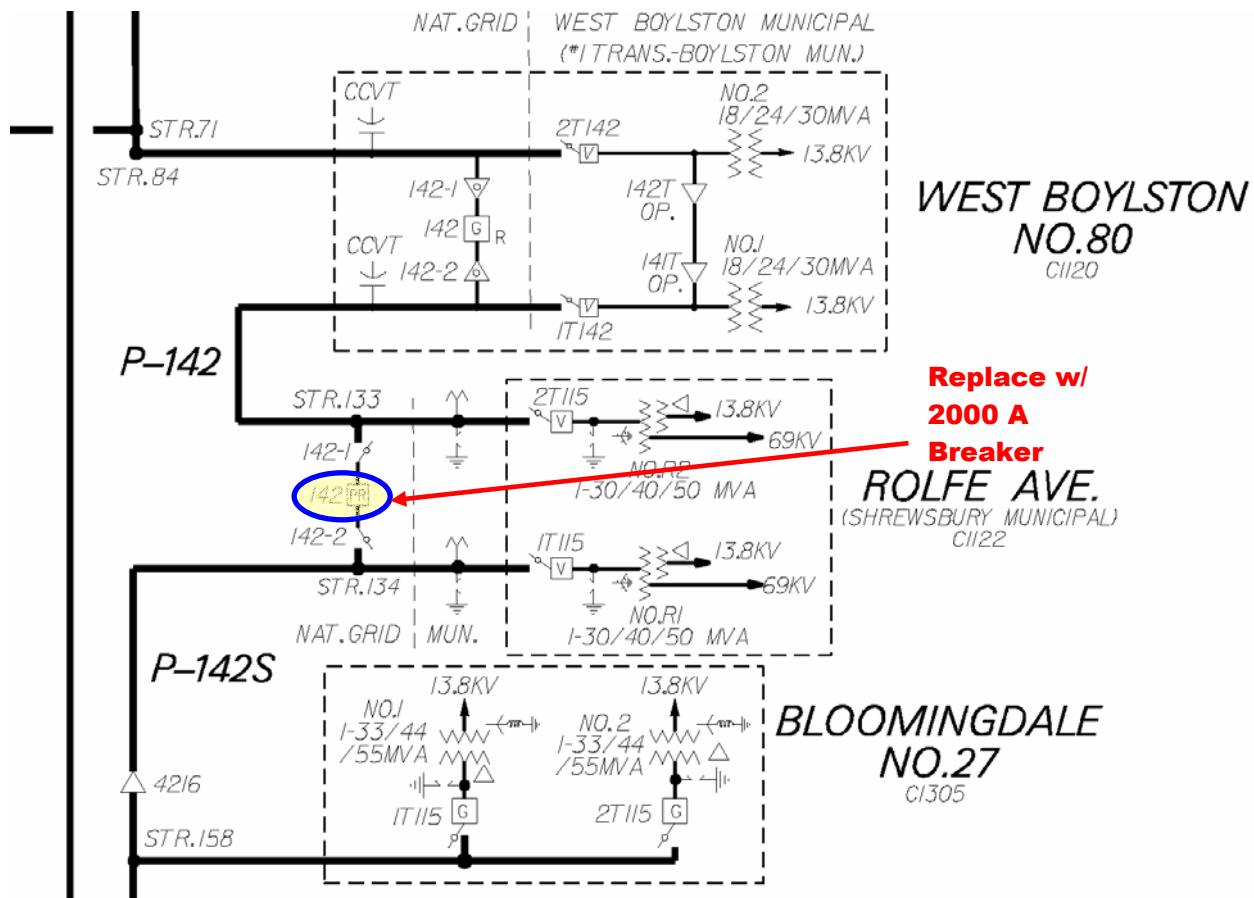
### 9.3.2.5 Upgrade Rolfe Avenue 115 kV Breaker

Loadflow results indicate that, with the Wachusett 345-115 kV transformers in-place, the Rolfe Avenue 115 kV breaker in-line with P-142 overloads for several contingencies. The existing breaker at Rolfe Ave has a nameplate rating of 1200 A. To eliminate the overload, this breaker needs to be replaced with at least a 2000 A breaker.

The following diagram shows the proposed upgrade.

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**Figure 9.19: Upgrade Rolfe Avenue 115 kV Breaker**



## Study-Grade Cost Estimates:

Substation	Transmission Line	Totals
Capital:	\$350,000	\$0
O&M:	\$6,000	\$0
Removal:	\$10,000	\$0
<b>Total:</b>	<b>\$366,000</b>	<b>\$0</b>
		<b>\$366,000</b>

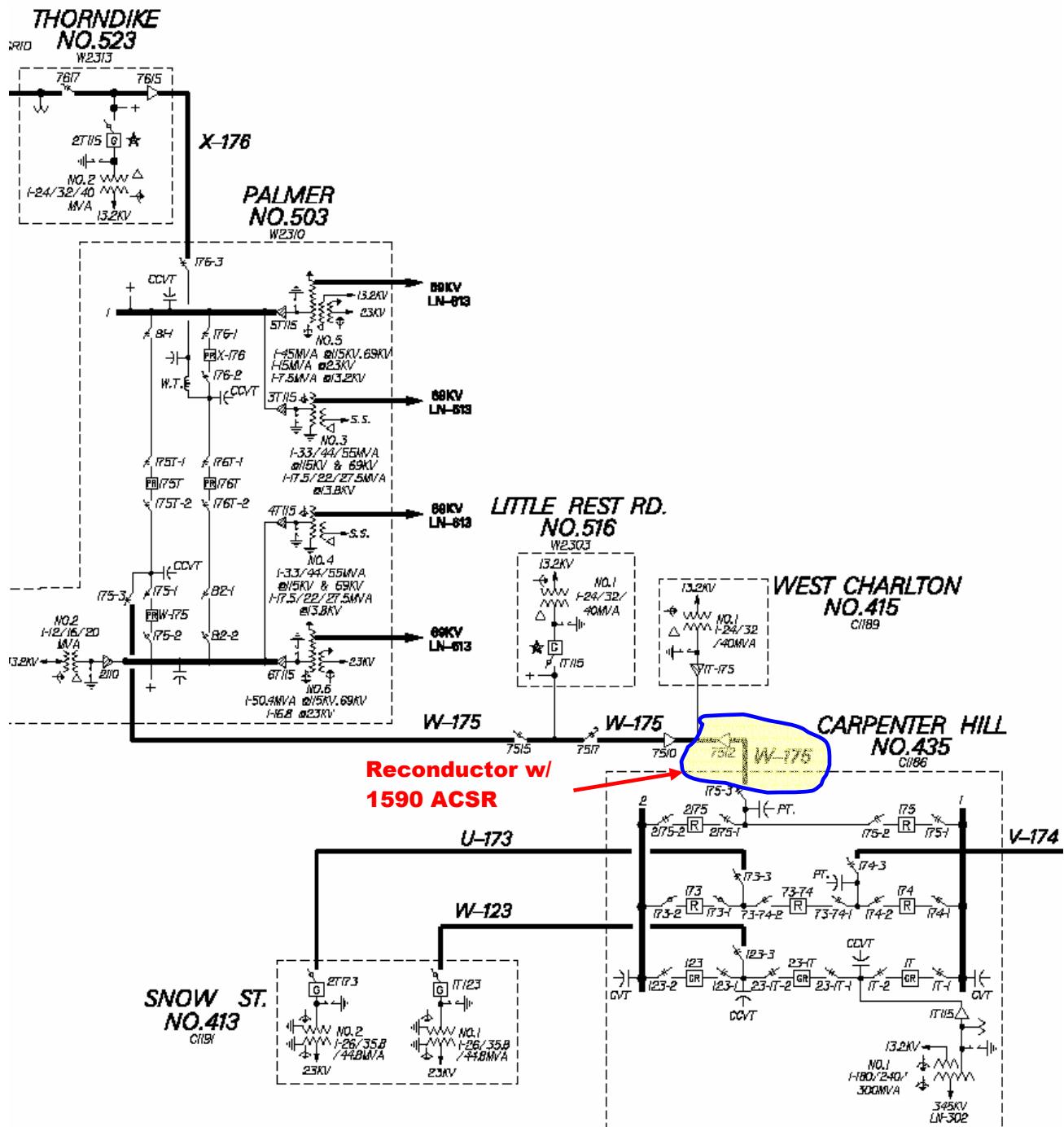
### 9.3.2.6 Reconducto W-175 [Carpenter Hill – W Charlton] 115 kV Line w/ 1590 ACSR

Loadflow results indicate that, with the Wachusett 345-115 kV transformers in-place, the W-175 115 kV line between Carpenter Hill and W Charlton overloads for several contingencies. To eliminate the overload, the existing 795 AI conductor needs to be replaced with at least 795 ACSR. However, reconductoring with 1590 ACSR only costs 36% (\$125k) more than reconductoring with 795 ACSR. Therefore 1590 ACSR is recommended.

The following diagram shows the proposed upgrade.

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Figure 9.20: Reconstructor W-175 [Carpenter Hill – W Charlton] w/ 1590 ACSR



## Study-Grade Cost Estimates

	Substation	Transmission Line	Totals
Capital:	\$ 0	\$405k	\$405k
O&M:	\$ 0	\$53k	\$53k
Removal:	\$ 0	\$17k	\$17k
<b>Total:</b>	<b>\$ 0</b>	<b>\$475k</b>	<b>\$475k</b>

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### **9.3.2.7 Protection Upgrades Required for Wachusett 345 kV Option**

Stability simulations (see Section 12) indicate that, with the Wachusett 345-115 kV transformers in-place, the following protection upgrades must be implemented:

- 1) The W Boylston 115 kV Protection system, owned by W Boylston Municipal, must be upgraded to meet NPCC criteria, since the New England Bulk Power System can become unstable if the W Boylston protection system fails to operate.
- 2) Single High-Speed (HS) protection system for the O-141N & P-142N 115 kV lines between Pratts Jct and Wachusett. Only one HS system is needed for O-141N & P-142N since an extreme contingency (115 kV BF at Wachusett, Z2 clearing from Pratts) causes system instability. (The fastest protection system is assumed to operate correctly for an extreme contingency).
- 3) Single High-Speed (HS) protection for the O-141N 115 kV line between Wachusett and Greendale. Only one HS system is required for O-141 [Wachusett - Greendale] since an extreme contingency (Z2 clearing followed by 115 kV breaker failure BF at Wachusett) results in system instability.
- 4) Redundant High-Speed (HS) protection for the P-142N 115 kV line between Wachusett and W Boylston. Redundant HS systems are needed for the P-142 line between Wachusett and W Boylston, since a design contingency (fault on P-142, Z2 clearing from Wachusett) results in system instability (fastest protection group is assumed to fail for design contingency).

#### **Study-Grade Cost Estimates**

	Pratts Jct Add Single HS Protection System for O-141N/P-142N	Greendale Add Single HS Protection for O-141N	W Boylston (MUNI) Upgrade to meet NPCC Criteria, Add Redundant HS protection for P-142N	Totals
Capital*:	\$250,000	\$175,000	\$425,000	\$850,000
O&M:	\$10,000	5000	\$15,000	\$30,000
Removal:	\$0	\$0	\$10,000	\$10,000
Total:	<b>\$260,000</b>	<b>\$180,000</b>	<b>\$450,000</b>	<b>\$890,000</b>

### **9.3.3 Quinsigamond Jct. - Install 2 new 345-115 kV Transformers (448 MVA)**

The third option investigated to eliminate the overload of Sandy Pd T1 and T2 was the addition of two new 345-115 kV autotransformers at Quinsigamond Jct in Boylston MA. Quinsigamond Jct is the location along the Sandy Pond – Millbury transmission corridor (includes 345 kV lines 343 & 314, and 115 kV lines O141 & P142) where the O-141 line splits off the Right of Way (ROW) and loops in and out of Greendale and Nashua St substations (Worcester), then back to the main ROW (a total of 10 circuit miles). The advantage of this option is that it converts the O-141 loop in and out of Greendale and Nashua St, into two radial 115 kV lines emanating from the Quinsigamond Jct substation. Converting this loop into two radial lines reduces transmission losses and improves voltage in the area.

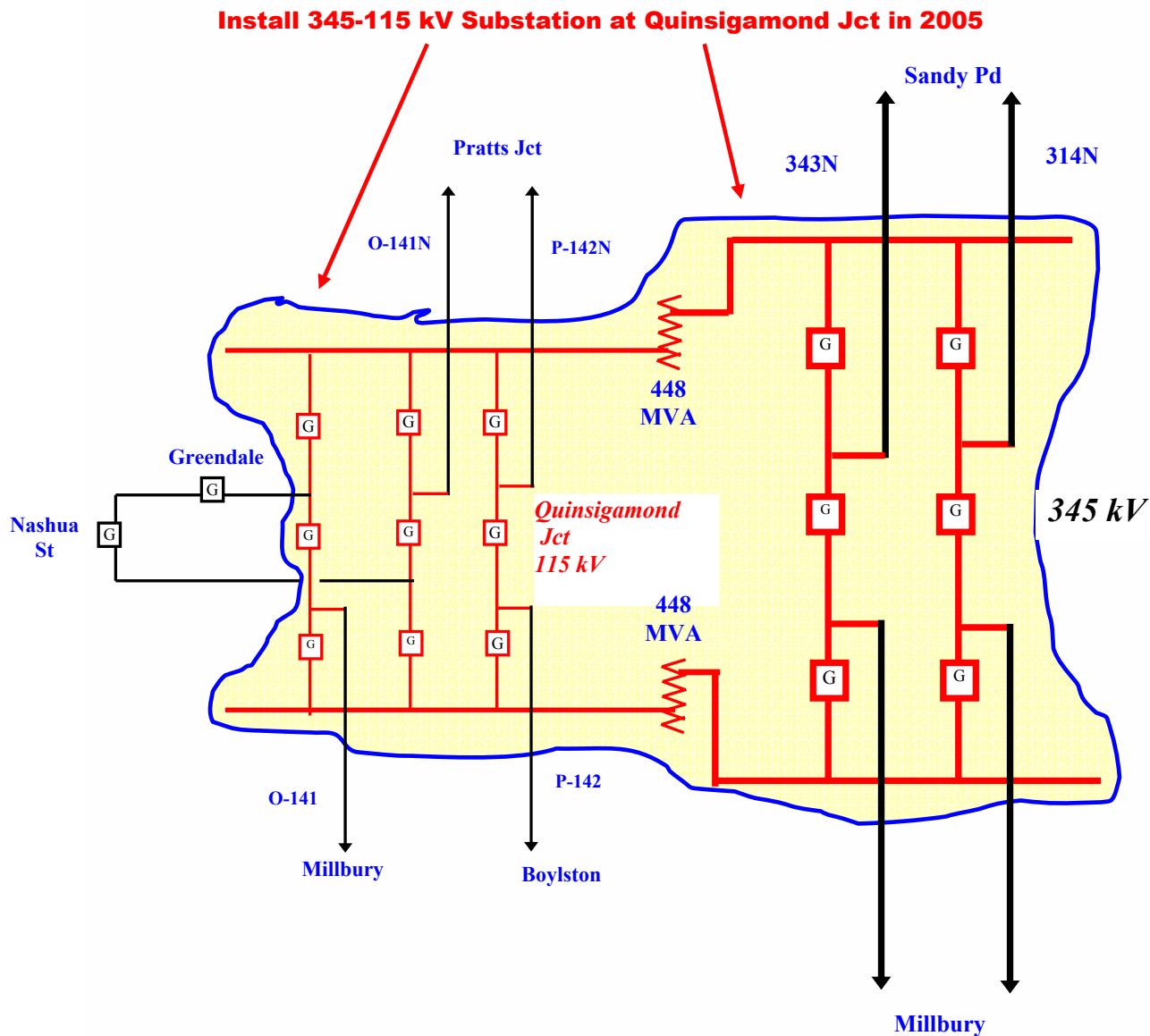
#### **345 kV Ring Bus:**

Like the Wachusett Option, loadflow results indicate that a 345 kV ring bus is needed at Quinsigamond Jct by year 2008. Although loadflow simulations indicate that the 345 kV ring bus at Quinsigamond Jct is not needed until 2008, results of a Present Value analysis indicate that cost savings of \$31k (in 2003 \$) can be realized by installing the ring bus with the 345-115 kV transformers in 2005, as apposed to waiting until 2008. Therefore, the 345 kV ring bus is proposed for 2005.

The following one-line diagram illustrates this option:

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**Figure 9.21: Build New 345-115 kV Substation at Quinsigamond Jct.**



## **Study-Grade Cost Estimates:**

	Substation	Transmission Line	Totals
	<b>345/115*</b>	<b>345kV Ring**</b>	
Capital:	\$23,500,000	\$2,000,000	\$2,200,000
O&M:	\$0,000	\$0,000	\$0
Removal:	\$0,000	\$0,000	\$0
<b>Total:</b>	<b>\$23,500,000</b>	<b>\$2,000,000</b>	<b>\$2,200,000</b>
			<b>\$27,700,000</b>

\*Includes \$1.5M to purchase land needed for new substation.

\*\*Includes two 345 kV breakers initially

\*\* Includes four additional 345 kV breakers for ring bus (\$150k per breaker)

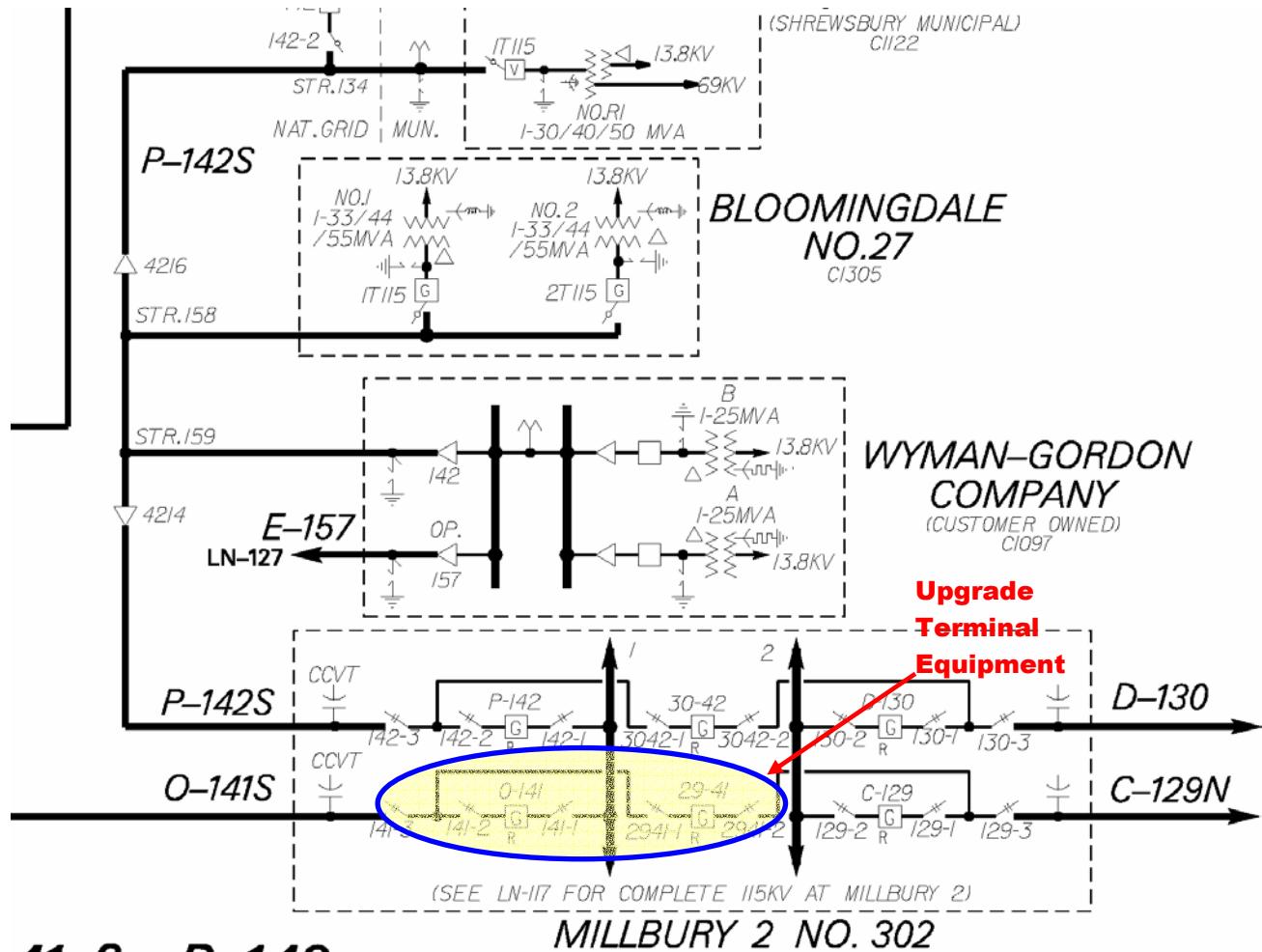
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### 9.3.3.2 Upgrade O-141S 115 kV Terminal Equipment at Millbury

Loadflow results indicate that the installation of the Quinsigamond Jct 345 kV autotransformers cause the O-141S 115 kV terminal equipment (bus conductor, switches, etc) at Millbury to overload during heavy load conditions for several contingencies. Therefore, the O-141S terminal equipment at Millbury needs to be upgraded when the Quinsigamond Jct 345 kV autotransformers are installed.

The following diagram illustrates the upgrades.

**Figure 9.22: Upgrade O-141S 115 kV Terminal Equipment at Millbury**



#### Study-Grade Cost Estimates:

	Millbury Substation	Transmission Line	Totals
Capital:	\$490,000	\$0	\$490,000
O&M:	\$0	\$0	\$0
Removal:	\$10,000	\$0	\$10,000
<b>Total:</b>	<b>\$500,000</b>	<b>\$0</b>	<b>\$500,000</b>

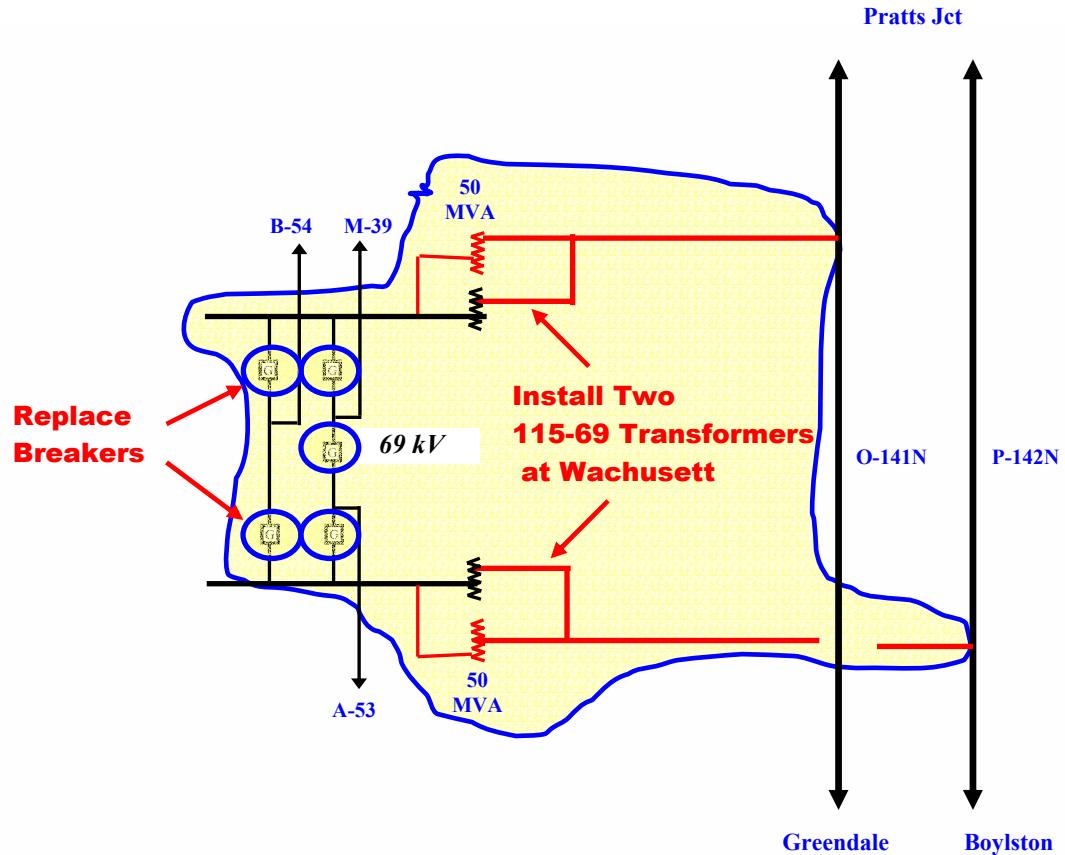
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### 9.3.3.3 Install 2 Additional 115-69 kV Transformers at Wachusett, and Replace 69kV Breakers

Loadflow results indicate that the installation of the Quinsigamond Jct 345 kV autotransformers cause the Wachusett 115-69 kV transformers to overload for several contingencies. Therefore, two additional 115-69 kV transformers at Wachusett are required when the Quinsigamond Jct 345 kV autotransformers are installed. With two additional 115-69 kV transformers at Wachusett however, all 69 kV breakers at Wachusett become over-dutied. Therefore all 69 kV breakers at Wachusett need to be replaced as well.

The following diagram shows the additions.

**Figure 9.23: Install 2 Additional 115-69 kV Transformers at Wachusett, and Replace 69kV Breakers**



#### Study-Grade Cost Estimates:

Wachusett Substation	Savings Realized from use of Millbury T1 and T2 @ Wachusett		Transmission Line	Totals
	Capital:	O&M:		
Capital:	\$5,000,000	(\$850,000)	\$0	\$4,150,000
O&M:	\$150,000	\$0	\$0	\$150,000
Removal:	\$100,000	\$0	\$0	\$100,000
Total:	\$5,250,000	(\$850,000)	\$0	\$4,400,000

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### 9.3.3.4 Reconducto M-39 69 kV line w/ 795 ACSR

As with Wachusett, adding 345 kV autotransformers at Quinsigamond Jct causes the existing M-39 69 kV circuit to overload for certain contingencies. Load flow results indicate that the circuit rating of M-39 should be increased to at least 170 MVA. This requires that M-39 be totally rebuilt. 6' triangular structures will be used. No terminal equipment upgrades will be required.

#### Study-Grade Cost Estimates:

	Stations	Lines	Totals
Capital:	\$170,000	\$1,000,000	\$1,170,000
O&M:	\$ 5,000	\$0	\$ 5,000
Removal:	\$ 5,000	\$0	\$ 5,000
<b>Totals:</b>	<b>\$180,000</b>	<b>\$1,000,000</b>	<b>\$1,180,000</b>

### 9.3.3.5 Upgrade Rolfe Avenue 115 kV Breaker

Like the Wachusett 345kV option, loadflow results indicate that the addition of the Quinsigamond 345 -115 kV transformers causes the Rolfe Avenue 115 kV breaker to overload for several contingencies. The existing breaker is at Rolfe Ave has a nameplate rating of 1200 A. To eliminate the overload, this breaker needs to be replaced with at least a 2000 A breaker.

#### Study-Grade Cost Estimates:

	Substation	Transmission Line	Totals
Capital:	\$350,000	\$0	\$350,000
O&M:	\$6,000	\$0	\$6,000
Removal:	\$10,000	\$0	\$10,000
<b>Total:</b>	<b>\$366,000</b>	<b>\$0</b>	<b>\$366,000</b>

### 9.3.3.6 Reconducto W-175 [Carpenter Hill – W Charlton] 115 kV Line w/ 795 ACSR

Loadflow results indicate that the installation of the Quinsigamond Jct 345 kV autotransformers cause the W-175 115 kV line [Carpenter Hill – W Charlton] to overload during heavy load conditions for loss of the 301/302 345 kV lines. This overload can be eliminated by reconductoring the overhead conductor with 795 ACSR. The resulting summer LTE rating of the circuit section will be 286 MVA.

#### Study-Grade Cost Estimates

	Substation	Transmission Line	Totals
Capital:	\$ 0	\$280k	\$280k
O&M:	\$ 0	\$53k	\$53k
Removal:	\$ 0	\$17k	\$17k
<b>Total:</b>	<b>\$ 0</b>	<b>\$350k</b>	<b>\$350k</b>

### 9.3.4 Common Items

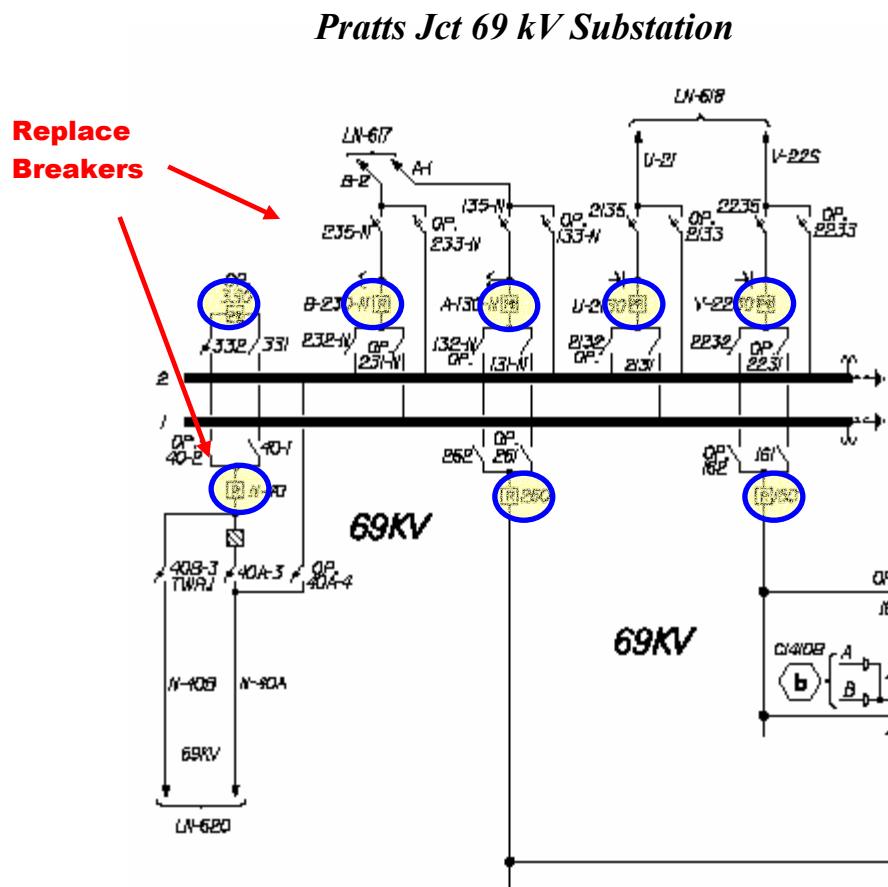
Installing 345-115 kV transformers at either Pratts Jct, Wachusett, or Quinsigamond Jct, requires several common upgrades. These are described in the following sections.

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## 9.3.4.1 Replace all Eight 69 kV Breakers at Pratts Jct

Adding 345 kV autotransformers at either Pratts Jct, Wachusett, or Quinsigamond Jct, overdues all eight 69 kV breakers at Pratts Jct. The following diagram shows the breakers that need to be replaced:

**Figure 9.24: Replace all eight 69 kV Breakers at Pratts Jct.**



## Study-Grade Cost Estimates

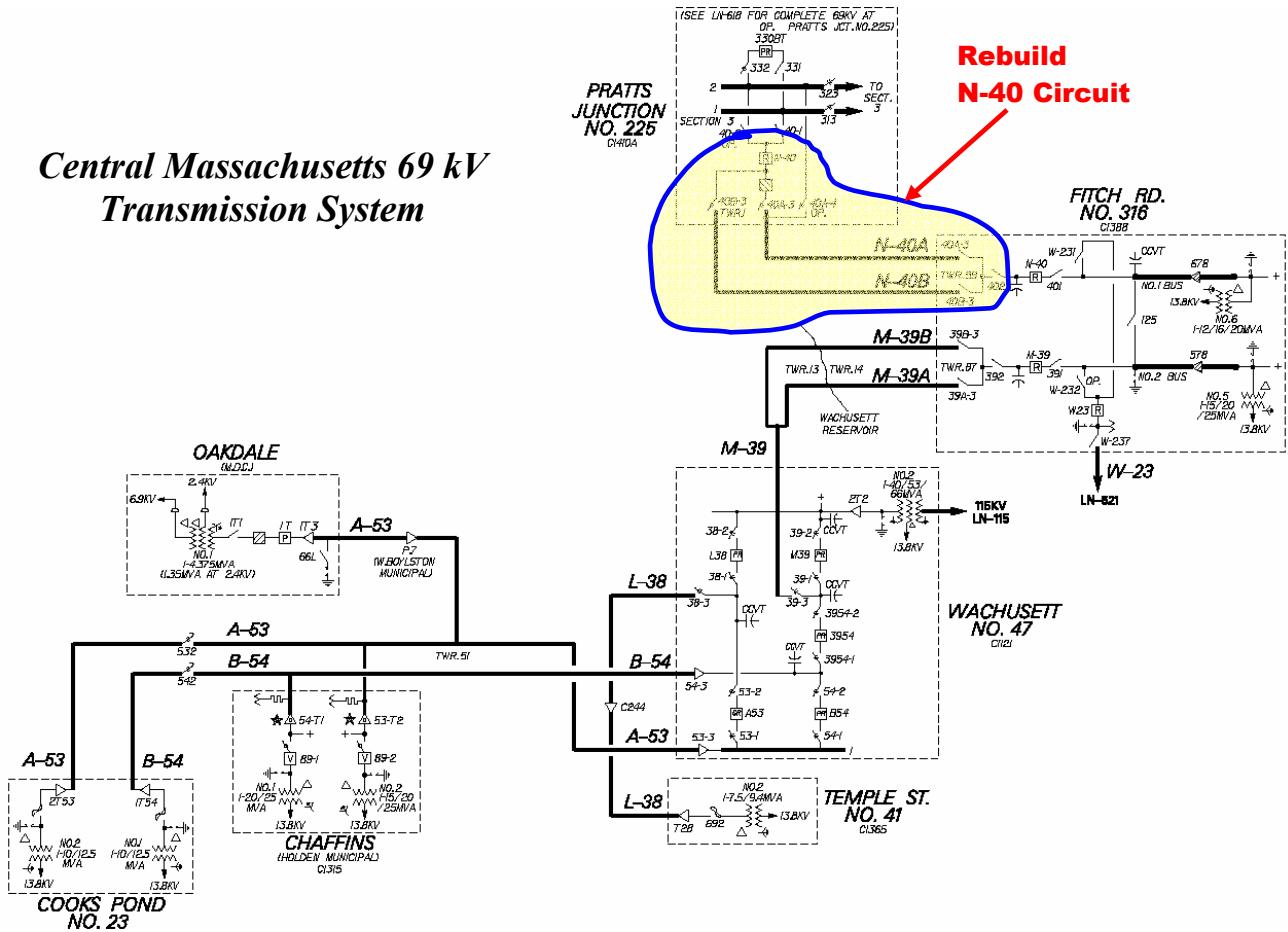
	Substation	Transmission Line	Totals
Capital:	\$770,000	\$0	\$770,000
O&M:	\$ 35,000	\$0	\$ 35,000
Removal:	\$ 35,000	\$0	\$ 35,000
Total:	<b>\$840,000</b>	<b>\$0</b>	<b>\$840,000</b>

## 9.3.4.2 Rebuild N-40 69 kV line

Adding 345 kV autotransformers at either Pratts Jct, Wachusett, or Quinsigamond Jct, causes the existing N-40 69 kV circuit to overload for certain contingencies. Load flow results indicate that the circuit rating of N-40 should be increased to at least 170 MVA. This requires that N-40 be totally rebuilt. 6' triangular structures will be used. Terminal equipment at Pratts Jct also needs to be upgraded. The following diagram shows the proposed upgrade.

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**Figure 9.25: Rebuild N-40 69 kV Circuit**



## Study-Grade Cost Estimates:

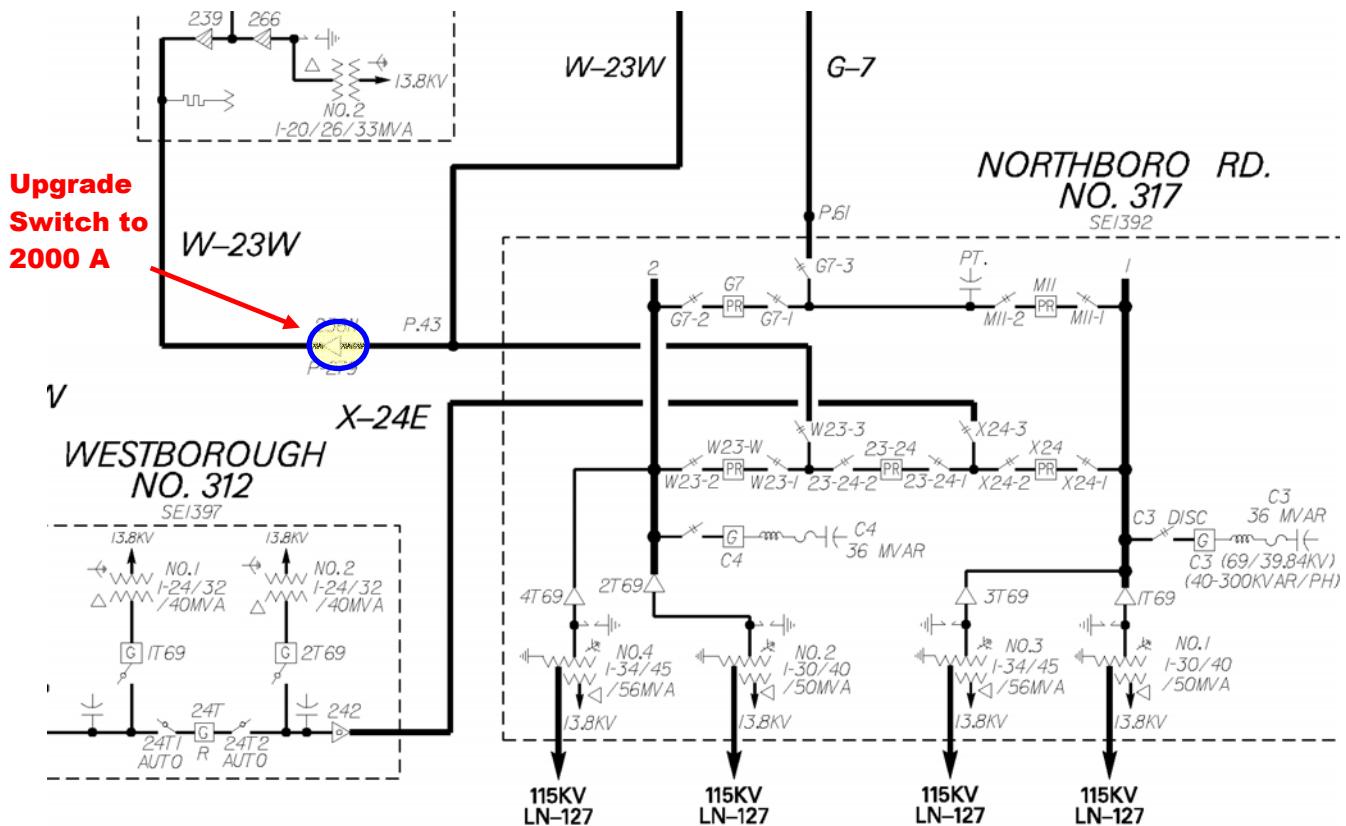
	Stations	Lines	Totals
Capital:	\$170,000	\$1,000,000	\$1,170,000
O&M:	\$ 5,000	\$0	\$ 5,000
Removal:	\$ 5,000	\$0	\$ 5,000
<b>Totals:</b>	<b>\$180,000</b>	<b>\$1,000,000</b>	<b>\$1,180,000</b>

### 9.3.4.3 Upgrade W-23E Disconnect Switch

Adding 345 kV autotransformers at either Pratts Jct, Wachusett, or Quinsigamond Jct, causes the existing W-23E 69 kV disconnect switch 236N to overload for certain contingencies. Load flow results indicate that the switch should have a nameplate rating of at least 2000 A. The following diagram shows the required upgrade.

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**Figure 9.26: Upgrade W-23E Disconnect Switch**



## Study-Grade Cost Estimates

	Substation	Transmission Line	Totals
Capital:	\$20,000	\$0	\$20,000
O&M:	\$ 0,000	\$0	\$ 0,000
Removal:	\$ 0,000	\$0	\$ 0,000
<b>Total:</b>	<b>\$20,000</b>	<b>\$0</b>	<b>\$20,000</b>

### 9.3.5 Financial Analysis – Present Value of Revenue Requirements

In order to determine the most cost effective solution for the Sandy Pond T1 & T2 overload problem, a financial analysis was conducted (see Appendix C). The financial analysis entailed a Present Value (PV) calculation of all Revenue Requirement streams for each of the three options. The three options are described again below:

1. Install 2 new 345-115 KV Transformers (448 MVA) at Pratts Jct:
  - b) Requires N40 & W23 to be converted to 115 KV in 2012, or:
  - c) Requires two additional 345-115 KV transformers to be installed in the Millbury Area, in 2012.
2. Install 2 new 345-115 KV Transformers (448 MVA) at Wachusett
3. Install 2 new 345-115 KV Transformers (448 MVA) at Quinsigamond Jct

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### 9.3.5.1 Net Present Value (NPV) of Revenue Requirements

The Net Present Value (NPV) of Revenue Requirements was calculated for each of the three options, and the results are provided in the following table.

**Table 9.1: Net Present Value (NPV) of Revenue Requirements**

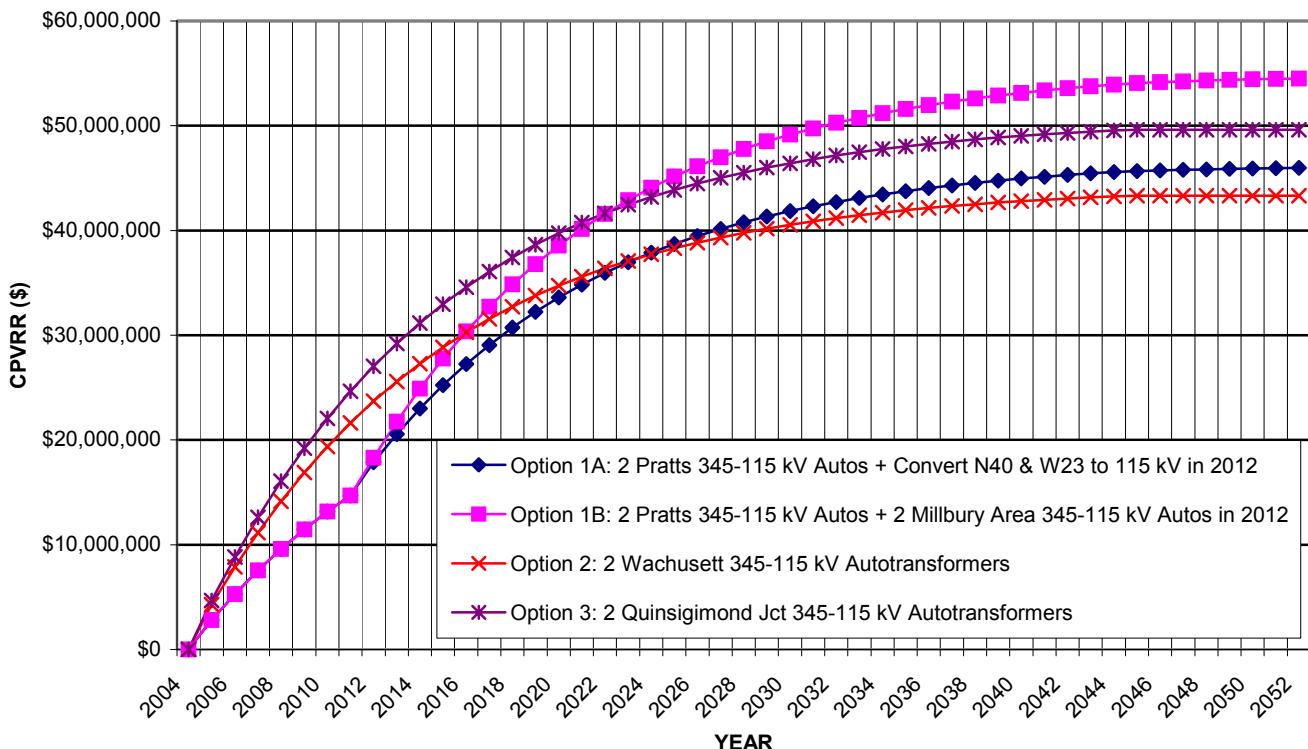
Transmission Reinforcement Options Developed to Eliminate Sandy Pond T1 & T2 Overload Problem	NPV of Rev Req't <u>2004 – 2052</u> (2003 \$)	Levelized Cost of Rev Req't <u>2004 – 2052</u> (2003 \$)
Option 1A: (Two Pratts 345-115 kV autos + Convert N40 + W23 to 115 kV in 2012)	\$44,532,426	\$3,211,007
Option 1B: (Two Pratts 345-115 kV autos + 2 Millbury Area 345-115 kV autos in 2012)	\$52,879,727	\$3,812,889
Option 2: (Two Wachusett 345-115 kV autos)	<b>\$42,301,570</b>	\$3,050,152
Option 3: (Two Quinsigamond Jct 345-115 kV autos)	\$48,461,315	\$3,494,300

As can be seen from the preceding table, Option 2 (Two Wachusett 345-115 kV autotransformers) requires the least amount of revenue (\$42.3M). Therefore, Option 2 is the least cost option, from an NPV perspective.

### 9.3.5.2 Cumulative Present Value of Revenue Requirements (CPV)

In addition to NPV, Cumulative Present Value (CPV) of revenue requirements was also calculated. The following figure shows the amount of revenue that must be obtained from customers, over a 40 year time period, on a cumulative basis, for each option.

**Figure 9.27: Cumulative Present Value (CPV) of Revenue Requirements**



As can be seen from the preceding figure, Option 2 requires the least amount revenue, on a cumulative basis. Although Option 2 requires more revenue than Option 1 during the early stages of the 48 year time period (i.e.

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from 2004 to 2016), the long-term revenue requirement of Option 2 is less, as indicated by the CPVRR at the end of the time period (i.e. 2052). Therefore, Option 2 is requires the least amount of revenue, in the long-term.

It should also be noted that although the cost of Option 1A (Pratts Jct – Two 345-115 kV autos + Convert N-40 & M-39 to 115 kV) is very close to that of Option 2, and possibly within the margin of error, the cost of Option 1B (Pratts Jct – Two 345-115 kV autos + Two 345-115 kV autos in Millbury area in 2012), is significantly higher than that of Option 2. Therefore, there exists substantial risk with Option 1, since the fallback option (1B) is very costly. For this reason, Option 1 was ruled out.

### 9.3.6 Recommendation

Based on both the NPV and CPV of Revenue Requirements for the three options, Option 2 (Two Wachusett 345-115 kV autotransformers) is least cost, and therefore recommended.

## 9.4 Alternatives Developed for Shrewsbury 69 kV Breaker (Over-Duty)

### 9.4.1 Do Nothing

According to MECO, Shrewsbury substation may no longer be needed following installation of a planned 115 kV underground cable between Vernon Hill substation and Bloomingdale substation. Therefore, Shrewsbury substation may be removed following installation of the cable. It could take as long as 4 years for the cable to be placed in service.

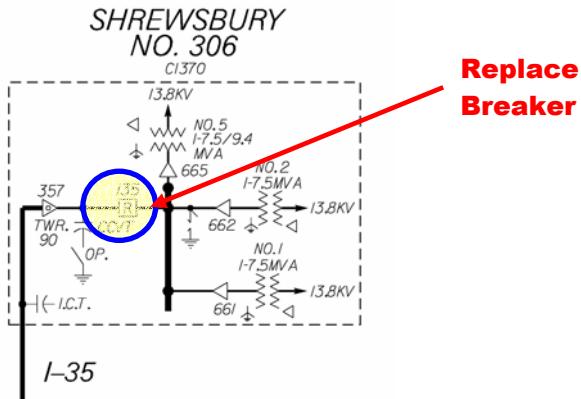
An alternative therefore is to live with the over-dutied breaker until it is no longer needed (4 years). Also, the exposure to the over-duty condition only exists for faults located between the 115-13.8kV transformers at Shrewsbury, and the breaker itself. Therefore, the exposure is very limited.

### 9.4.2 Replace Shrewsbury 69 kV Breaker I-35

A second alternative is to upgrade the breaker, knowing that it may be no longer needed in 4 years. Although the breaker may be removed, it will have some salvage value and can be used at another location if needed.

The following diagram illustrates the upgrade.

Figure 9.1: Replace Shrewsbury 69 kV Breaker I-35



### Study-Grade Cost Estimates

	Substation	Transmission Line	Totals
Capital:	\$ 400k	\$ 0	\$ 400k
O&M:	\$ 6k	\$ 0	\$ 6k
Removal:	\$ 20k	\$ 0	\$ 20k
Total:	\$ 426k	\$ 0	\$ 426k

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### 9.4.3 Recommendation

Due to the relatively long exposure to an over-duty condition (4 years), and the safety issues associated with that exposure, it is recommended that the replaced (option 2), and then salvaged after 4 years of service.

### 10.0 POST-UPGRADE SHORT CIRCUIT RESULTS (Wachusett Option Only)

The following table provide short-circuit results for the recommended post-upgrade system (Wachusett T345 kV), including all other recommended upgrades

#### 10.1 Post-Upgrade Short-Circuit Results

**Table 10.1: Post-Upgrade Short-Circuit Results**

Substation	Delivery Voltage (kV)	3-PH Peak RMS (kA)	1-PH Peak RMS (kA)	Breaker I.C. (kA)
Ayer	115	20.4	15.6	40.0
Ayer	69	10.1	9.8	19 - 22
				40.0
Boylston	115	32.4	26.3	50 (proposed – must be replaced to meet NPCC criteria)
Fitch Rd	69	20.6	15.4	40.0
Greendale	115	17.4	12.5	25.1
Millbury 5	69	19.9	19.4	31.5
Millbury 2	115	28.0	21.3	50.0
Millbury 3	345	33.5	25.0	37.0 - 50.0
Nashua St	115	14.5	10.5	40.0
Northboro Rd	115	14.1	10.7	25.1 - 43.0
Northboro Rd	69	17.7	15.9	21.0 - 31.5
Pratts Junction	115	28.2	25.3	40.0
Pratts Junction	69	25.2	25.2	19.0 - 21.0* (existing) 40 (planned)
Rolfe Ave (Shrewsbury)	115	19.3	14.0	17.6 40 (planned)
Sandy Pond	115	39.7	43.8	43-63**
Sandy Pond	345	28.5	23.5	50.0
Shrewsbury	69	9.0	7.3	7.5 (existing) 19 (planned)
Wachusett	69	24.0	24.1	19.0 - 20.0* (existing) 40 (planned)
Wachusett	115	40.8	37.8	63 (planned)
Wachusett	345	29.4	21.2	50 (planned)
Webster St	115	8.6	7.2	31.4
Westboro	69	11.9	7.4	22.0
Woodside	69	12.7	7.4	31.5

\*All Breakers at subject substation are overdutied.

\*\*Taking into account branch contributions, breakers are not overdutied.

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## 11.0 STABILITY ANALYSIS (Wachusett Option Only)

This section provides details on the stability analysis conducted for the recommended Option 2 (Wachusett 345-115 kV transformers). Stability analysis for the other two options (Pratts Jct 345 kV and Quinsigamond Jct 345 kV), were not conducted in full.

### 11.1 Base Case Load Flows

**Table 11.1: Base Case Details – Stability Analysis**

Case Name	Year	Load Level	NEPOOL Load (GW)	NEW ENGLAND INTERFACE TRANSFERS (MW)						
				E-W (2400)	SEMA/RI (2200)	PH II (2000)	NB-NE (700)	ME-NH (1400)	NNE-Sc (2550)	Sbrk-South (1400)
05ll-ns	2005	Light Load	11.6	2440	874	0	698	1404	2547	1302
05ll-semari				2403	2403	0	698	323	1183	847
05pk-ns		Summer Peak	25.4	2403	1713	2000	701	1417	2574	1405

More detailed summaries for both cases are given in Appendix B of this report.

### 11.2 Contingency List

**Table 11.2: Contingency List – Stability Analysis**

Name	Type	Description	Clearing Times
343-SP	Normal	3ph fault on 343 line @ Sandy Pd 345 kV, normal clearing	4.5 cy at Millbury & Sandy Pd, 5.5 cy @ Wach 115 kV.
343-ML	Normal	3ph fault on 343 line @ Millbury 345 kV, normal clearing	4.5 cy at Millbury & Sandy Pd, 5.5 cy @ Wach 115 kV.
ML1402	Extreme	Millbury 1402 BF (IPT), 3ph fault on 302 line @ Millbury 345 kV.	4cy @ Carp HI & Ludlow, 10 cy @ Millbury, 11 cy @ SP, 12 cy @ Wach
ML314	Extreme	Millbury 314 BF (IPT), 3ph fault on 323 line @ Millbury 345 kV.	4 cy @ WM, 9 cy @ Millbury, 10 cy @ SP, 11 cy @ Wach
SP2643	Extreme	Sandy Pd 2643 BF, 3ph fault on 326 line at Sandy Pd 345 kV.	4cy @ Scobie, 5cy @ Lawr, 11cy @ SP, 12cy @ ML 13cy @ Wach
P142N-Z1	Normal	3ph fault on P142N 115 kV line @ Wach, Zone 1 Clearing at Wach, Zone 2 Clearing at Pratts.	6 cy at Wach 115 kV, 42 cy at Pratts 115 kV.
P142N-Z2	Normal	3ph fault on P142N 80% down the line from Wachusett towards Pratts, Zone 2 Clearing at Wach, Zone 1 Clearing at Pratts.	30 cy at Wach 115 kV, 6 cy at Pratts 115 kV.
P142-Z1	Normal	3ph fault on P142N 115 kV line @ Wach, Zone 1 Clearing at Wach, Zone 2 Clearing at W Boylston.	6 cy at Wach 115 kV, 30 cy at W Boylston 115 kV.
P142-Z2	Normal	3ph fault on P142N 80% down the line from Wachusett towards W Boylston, Zone 2 Clearing at Wach, Zone 1 Clearing at W Boylston.	30 cy at Wach 115 kV, 6 cy at W Boylston 115 kV.
WA142N	Extreme	3ph fault on P142N line at Wachusett, Failure of new Wachusett P142N 115 kV breaker. Z2 clearing from Pratts,	15 cy at Wachusett 115 kV, 30 cy at PJ 115 kV.
WA142N-DTT	Extreme	3ph fault on P142N line at Wachusett, Failure of new Wachusett P142N 115 kV breaker. Direct Transfer Trip (DTT) @ Pratts,	15 cy at Wachusett 115 kV, 16 cy @ Pratts Jct
WA142N-HS	Extreme	3ph fault on P142N line at Wachusett, Failure of new Wachusett P142N 115 kV breaker. High Speed clearing from Pratts,	6 cy at PJ 115 kV, 15 cy at Wachusett 115 kV.
WA141S-Z2	Extreme	3ph fault 80% down O141S line from Wachusett towards Greendale, Failure of new Wachusett P-142S 115 kV breaker. Z2 clearing from Wachusett,	6 cy at Greendale 115 kV, 39 cy at Wachusett 115,
WA141S-Z2-HS	Extreme	3ph fault 80% down O141S line from Wachusett towards Greendale, Failure of new Wachusett P-142S 115 kV breaker. High Speed (HS) clearing from Wachusett,	6 cy at Greendale 115 kV, 15 cy at Wachusett 115,
WA141N-TIE	Extreme	3ph fault on O141N line at Wachusett, Failure of new Wachusett 141 Tie 115 kV breaker. Z2 clearing from Pratts & Greendale.	15 cy at Wachusett 115 kV, 30 cy at Greendale, 30 cy at Pratts Jct.

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Name	Type	Description	Clearing Times
WA142N-TIE	Extreme	3ph fault on P142N line at Wachusett, Failure of new Wachusett 142 Tie 115 kV breaker. High speed clearing from W Boylston, Z2 clearing from Pratts.	15 cy at Wachusett 115 kV, 16 cy at W Boylston, 30 cy at Pratts Jct.
WB-BPS	Normal	3ph fault at W Boylston 115 kV bus, no clearing	-
WB-BPS-Z2	Normal	3ph fault at W Boylston 115 kV bus, Z2 clearing from Wachusett and Rolfe Avenue.	30 cy from Wachusett and Rolfe Ave.
GD-BPS	Normal	3ph fault at Greendale 115 kV bus, no clearing	-
Nash-BPS	Normal	3ph fault at Nashua St 115 kV bus, no clearing	-
RF-BPS	Normal	3ph fault at Rolfe Ave 115 kV bus, no clearing	-
RF-BPS-Z2	Normal	3ph fault on P142S line @ Rolfe Ave. Z2 clearing from W Boylston and Millbury.	30cy at Millbury 30 cy at W Boylston
RF-BPS-Z3-Z1	Normal	3ph fault on P142S line between Rolfe Ave and Millbury (125% from W Boylston sub). Z3 clearing from W Boylston, Z1 clearing from Millbury.	6cy at Millbury 186 cy at W Boylston
WA-69-BPS	Normal	3ph fault at Wachusett 69 kV bus, no clearing	-
Ayer-BPS	Normal	3ph fault at Ayer 115 kV bus, no clearing	-
Ayer-BPS-Z2	Normal	3ph fault at Ayer 115 kV bus, Zone 2 clearing from both Sandy Pond and Pratts Jct.	30 cy at Pratts Jct and Pratts Jct
Ayer-bps-Z2-Z3	Normal	3ph fault at Ayer 115 kV bus, Zone 2 clearing from Pratts Jct, Z3 clearing from Sandy Pd.	30 cy at Pratts Jct, 50 cy at Sandy Pd
Ayer-bps-Z3-Z1	Normal	3ph fault at Ayer 115 kV bus, Zone 3 clearing from Pratts Jct, Z1 clearing from Sandy Pd.	66 cy at Pratts Jct, 6 cy at Sandy Pd
PJ-69-BPS	Normal	3ph fault at Pratts Jct 69 kV bus, no clearing	-
SR142	Extreme	Sherman Rd 142 BF (IPT), 3ph fault on 328 @ Sherman Rd.	4 cy at Sherman Rd, downgrade to 1ph fault, 9.5 cy at Sherman Rd, 10.5 cy at ANP Blackstone
SC9126	Extreme	Scobie 9126 BF (IPT), 3ph fault on 326 @ Scobie.	4 cy at sandy Pd, downgrade to 1ph fault, 8 cy at Scobie, 9 cy at Buxton
SB294	Extreme	Seabrook 294 BF (IPT), 3ph fault on 394 @ seabrook,	4 cy at Tewksbury, & Ward Hill, downgrade to 1ph fault,.. 8 cy at Seabrook.
NF3T	Extreme	Northfield 3T BF (IPT), 3ph fault on 312 @ Northfield.	4 cy at Alps, downgrade to SLG at Northfield, 5 cy at Berkshire 115 kV, 8.7 cy at Northfield,11.5 cy at VY.
CD2T	Extreme	Card St 2T BF (IPT), 3ph fault on 368 line @ Card St.	4cy @ Manchester, 11.2 @ Card St, 13.9 cy @ Millstone,
396	normal	3ph fault on 396 345 kV line @ Orrington, Normal Clearing.	4 cy @ Orrington, Keswick, and Chester.
VY381	Normal	Vermont Yankee 381 BF, 1ph fault on 381 @ VY,	4 cy @ Northfield, 10 cy @ VY 345 and 115 kV.
PHII	Extreme	Bipolar loss of Sandy Pond HVDC due to DC side contingency. Communication failure – Trip Sandy Pd Cap banks after 550 ms.	0 cy: Trip Phase II, both poles, 550 ms: Trip Sandy Pd Cap banks

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### 11.3 Post-Upgrade Results

**Table 11.3: Results of Stability Analysis (Wachusett Option Only)**

Name	Type	Description	Results for each Case (✓ Stable X Unstable)		
			05II-ns	05II-semari	05-peak-ns
343-SP	Normal	3ph fault on 343 line @ Sandy Pd 345 kV, normal clearing	✓	✓	✓
343-ML	Normal	3ph fault on 343 line @ Millbury 345 kV, normal clearing	✓	✓	✓
ML1402	Extreme	Millbury 1402 BF (IPT), 3ph fault on 302 line @ Millbury 345 kV.	✓	✓	✓
ML314	Extreme	Millbury 314 BF (IPT), 3ph fault on 323 line @ Millbury 345 kV.	✓	✓	✓
SP2643	Extreme	Sandy Pd 2643 BF, 3ph fault on 326 line at Sandy Pd 345 kV.	✓	✓	✓
P142N-Z1	Normal	3ph fault on P142N 115 kV line @ Wach, Zone 1 Clearing at Wach, Zone 2 Clearing at Pratts.	✓	✓	✓
P142N-Z2	Normal	3ph fault on P142N 80% down the line from Wachusett towards Pratts, Zone 2 Clearing at Wach, Zone 1 Clearing at Pratts.	✓	✓	✓
P142-Z1	Normal	3ph fault on P142N 115 kV line @ Wach, Zone 1 Clearing at Wach, Zone 2 Clearing at W Boylston.	✓	✓	✓
P142-Z2	Normal	3ph fault on P142N 80% down the line from Wachusett towards W Boylston, Zone 2 Clearing at Wach, Zone 1 Clearing at W Boylston.	X	X	✓
WA142N	Extreme	3ph fault on P142N line at Wachusett, Failure of new Wachusett P142N 115 kV breaker. BF clearing at Wachusett, Sandy Pd and Millbury 345 kV, Z2 clearing from Pratts.	X	X	✓
WA142N-DTT	Extreme	3ph fault on P142N line at Wachusett, Failure of new Wachusett P142N 115 kV breaker. DTT @ Pratts,	✓*	✓*	✓
WA142N-HS	Extreme	3ph fault on P142N line at Wachusett, Failure of new Wachusett P142N 115 kV breaker. BF clearing at Wachusett, Sandy Pd and Millbury 345 kV, High Speed clearing from Pratts,	✓	✓	✓
WA141S-Z2	Extreme	3ph fault 80% down O141S line from Wachusett towards Greendale, Failure of new Wachusett P-142S 115 kV breaker. Z1 clearing from Greendale BF+Z2 clearing at Wachusett 115 kV	X	X	✓
WA141S-Z2-HS	Extreme	3ph fault 80% down O141S line from Wachusett towards Greendale, Failure of new Wachusett P-142S 115 kV breaker. Z1 clearing from Greendale, BF + High Speed clearing at Wachusett 115 kV	✓	✓	✓
WA141N-TIE	Extreme	3ph fault on O141N line at Wachusett, Failure of new Wachusett 141 Tie 115 kV breaker. Z2 clearing from Pratts & Greendale.	✓	✓	✓
WB-BPS	Normal	3ph fault at W Boylston 115 kV bus, no clearing	X	X	X
WB-BPS-Z2	Normal	3ph fault at W Boylston 115 kV bus, Z2 clearing from Wachusett and Rolfe Avenue.	X	X	✓
GD-BPS	Normal	3ph fault at Greendale 115 kV bus, no clearing	✓	✓	✓
Nash-BPS	Normal	3ph fault at Nashua St 115 kV bus, no clearing	✓	✓	✓
RF-BPS	Normal	3ph fault at Rolfe Ave 115 kV bus, no clearing	X	X	✓
RF-BPS-Z2	Normal	3ph fault on P142S line @ Rolfe Ave. Z2 clearing from W Boylston and Millbury.	✓	✓	✓
RF-BPS-Z3	Normal	3ph fault on P142S line between Rolfe Ave and Millbury (125% from W Boylston sub). Z3 clearing from W Boylston, Z1 clearing from Millbury.	✓	✓	✓
WA-69-BPS	Normal	3ph fault at Wachusett 69 kV bus, no clearing	✓	✓	✓
Ayer-BPS	Normal	3ph fault at Ayer 115 kV bus, no clearing	X	X	✓
Ayer-BPS-Z2	Normal	3ph fault at Ayer 115 kV bus, Zone 2 clearing from both Sandy Pond and Pratts Jct.	✓	✓	✓
Ayer-bps-Z2-Z3	Normal	3ph fault at Ayer 115 kV bus, Zone 2 clearing from Pratts Jct, Z3 clearing (50 cy) from Sandy Pd.	✓	✓	✓
Ayer-bps-Z3-Z1	Normal	3ph fault at Ayer 115 kV bus, Zone 3 clearing from Pratts Jct, Z1 clearing from Sandy Pd.	✓	✓	✓
PJ-69-BPS	Normal	3ph fault at Pratts Jct 69 kV bus, no clearing	✓	✓	✓
FGE-BPS	Normal	3ph fault at Flagg Pd 115 kV bus, no clearing	✓	✓	✓

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Name	Type	Description	Results for each Case (✓ Stable X Unstable)		
			05II-ns	05II-semari	05-peak-ns
SR142	Extreme	Sherman Rd 142 BF (IPT), 3ph fault on 328 @ Sherman Rd.	✓	✓	✓
SC9126	Extreme	Scobie 9126 BF (IPT), 3ph fault on 326 @ Scobie.	✓	✓	✓
SB294	Extreme	Seabrook 294 BF (IPT), 3ph fault on 394 @ seabrook,	✓	✓	✓
NF3T	Extreme	Northfield 3T BF (IPT), 3ph fault on 312 @ Northfield.	✓	✓	✓
CD2T	Extreme	Card St 2T BF (IPT), 3ph fault on 368 line @ Card St.	✓	✓	✓
396	normal	3ph fault on 396 345 kV line @ Orrington, Normal Clearing.	✓	✓	✓
VY381	Normal	Vermont Yankee 381 BF, 1ph fault on 381 @ VY,	✓	✓	✓
PHII	Extreme	Bipolar loss of Sandy Pond HVDC due to DC side contingency. Communication failure – Trip Sandy Pd Cap banks after 550 ms.	-	-	✓

\* Marginally stable – Apparent Impedance at Keswick almost goes through GCX characteristic, before tripping 396 345 kV line. If impedance would have gone through the GCX characteristic, 396 would not have tripped, and NEPOOL system would have split in the Maine/NH area.

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### 11.4 Discussion

Stability results indicate that the following stability upgrades need to be implemented for the Wachusett Option.

- 1.) **High Speed Protection systems** must be installed for all four 115 kV lines emanating from Wachusett substation: P-142N (Wachusett – Pratts Jct), O-141N (Wachusett – Pratts Jct), P-142 (Wachusett – W Boylston), and O-141N (Wachusett – Pratts Jct). The reasons for this are as follows:
  - **P-142N (Wachusett – Pratts Jct)** – A single High-speed protection system is needed for this line since the Breaker Failure contingency, WA142N, is unstable. This contingency involves Zone 2 clearing from Pratts Jct. With high-speed clearing from Pratts Jct, the response is stable, as the results of contingency WA142N-HS show.
  - **O-141N (Wachusett – Pratts Jct)** – A Single High-speed protection system is needed for this line since it is in parallel with P-142N. Therefore, the results obtained for P-142N, justify high-speed protection for O-141N.
  - **P-142 (Wachusett – W Boylston)** – A redundant High-speed protection system is needed for this line since the P142-Z2 contingency is unstable. This contingency involves Zone 2 clearing from Wachusett. With high-speed clearing from Wachusett, the response is stable, as the results of contingency P142-Z1 show.
  - **O-141 (Wachusett – Greendale)** – A single High-speed protection system is needed for this line since the Breaker Failure contingency, WA141S-Z2, is unstable. This contingency involves Zone 2 clearing from Wachusett. With high-speed clearing, the response is stable, as the results of contingency WA141S-Z2-HS show.
- 2.) **W Boylston 115 kV substation must be upgraded to meet Bulk Power system requirements** (i.e. Redundant and separate protection systems must be installed). The reasons for this are as follows:
  - **W Boylston 115kV** – Must be upgraded to meet Bulk Power requirements since the WB-bps-Z2 contingency is unstable. This contingency involves the failure of the lone protection system at W Boylston substation, with Zone 2 backup clearing from both Wachusett and Rolfe Ave. Since Zone 2 clearing from both ends is the best case scenario in terms of stability, it follows that a second protection system is required to eliminate this contingency.

**Table 11.4: Stability Upgrades Required for Wachusett Option**

Stability Upgrades Required	Study-Grade Cost Estimate
O-141N and P-142N [Wachusett – Pratts Jct] - Install High Speed Protection	\$260,000
O-141 [Wachusett – Greendale] - Install High Speed Protection	\$180,000
W Boylston Substation – Upgrade to meet Bulk Power System Requirements. Install High-Speed protection for P-142 [Wachusett – W Boylston].	\$450,000
Total:	\$890,000

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### **APPENDIX A**

#### **Case Summaries – Steady State Analysis**























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### **APPENDIX B**

#### **Case Summaries – Stability Analysis**





